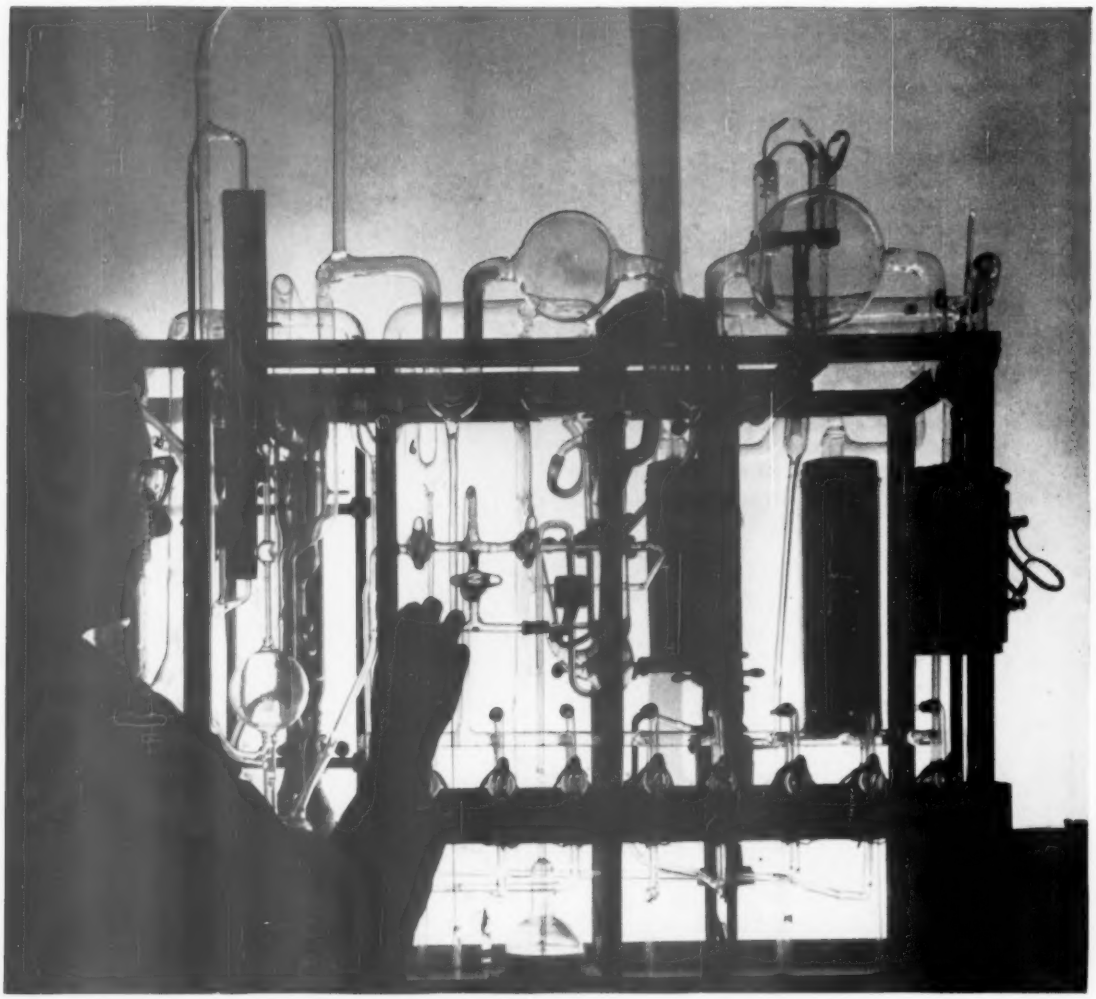
NUCLEONICS

February 1953

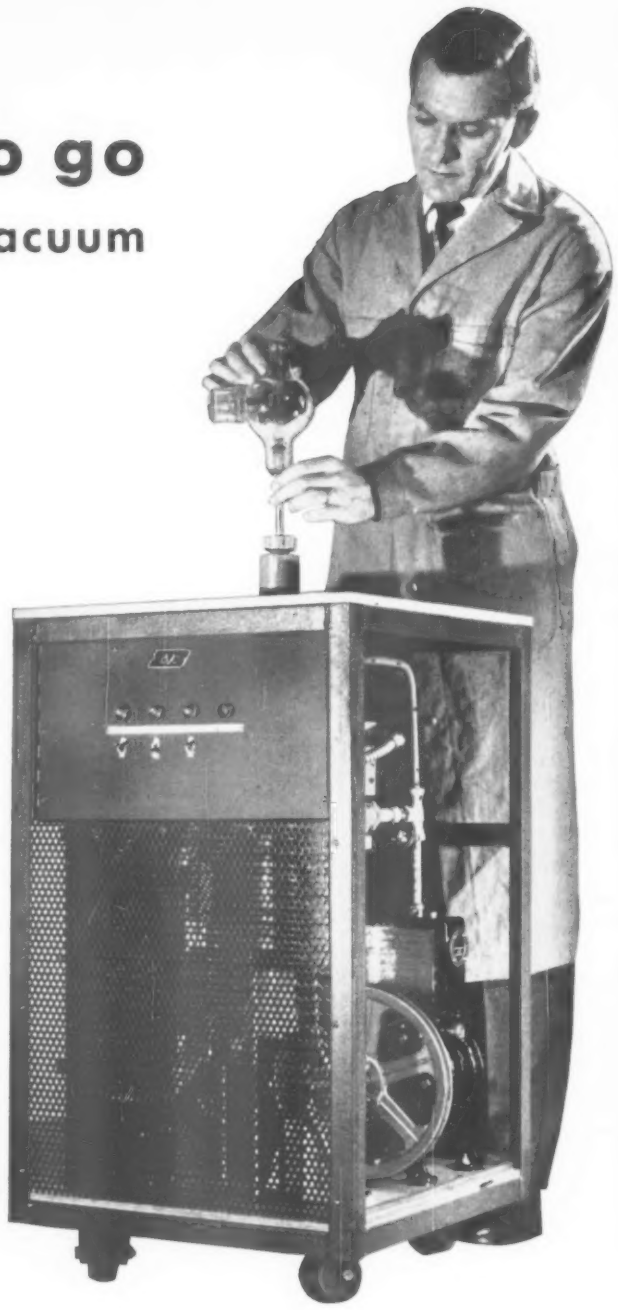


Precision vacuum-fusion apparatus is used at Battelle Memorial Institute to determine O and N (1 ppm) and H (0.1 ppm) in metals. Studies aid control of fabrication and gas evolution during irradiation from U, Th, Zr, Ti, Mo, and other metals used in reactors

A McGRAW-HILL PUBLICATION ★ SEVENTY-FIVE CENTS

Ready to go

CVC's portable high vacuum pumping unit



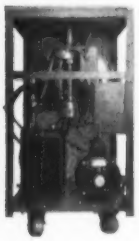
Say you want to produce a vacuum on the order of 1×10^{-6} mm Hg in an experimental vessel such as an electron tube.

With this compact, "packaged" unit all you do is wheel it in (it's mounted on casters), connect it to electrical and water outlets and you're ready to go. Attach the vessel you wish to exhaust, throw a switch and in a few minutes you have your vacuum.

This new unit is CVC's Laboratory Tube-Exhaust Unit, Type MCF-60. Completely self-contained, it includes a mechanical pump, a three-stage fractionating oil diffusion pump, and semi-automatic controls.

The entire unit is mounted in a steel frame work which has a transite top so that an oven can be lowered over the vessel for bakeout or annealing. Provisions can be made for pressure measurement. And it requires little experience to keep the unit in steady use.

This unit can save you much costly time and technical manpower in solving the numerous problems involved in fitting together the components of a high vacuum system that would do a similar job. To find out more about this unit or any equipment for the production, measurement and use of high vacuum, write to **Consolidated Vacuum Corporation, Rochester 3, N. Y.** (A subsidiary of Consolidated Engineering Corporation, Pasadena, Calif.) Sales offices: Menlo Park, Calif. • Chicago, Ill. • Camden, N. J. • New York, N. Y.



Designed for long, trouble-free operation, CVC's Laboratory Tube-Exhaust Unit, Type MCF-60 is readily accessible from the rear. A single mechanical pump serves both for rough pumping and backing the diffusion pump. A cyclic solenoid valve provides semi-automatic operation. A safety device isolates the diffusion pump from the tube port whenever pressures become too high.

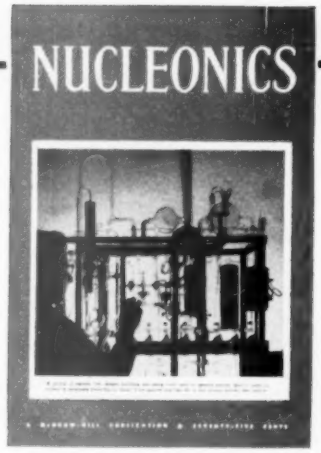
CVC

formerly DPi Vacuum Equipment Dept.

Consolidated Vacuum Corporation

high vacuum research and engineering

Want more information? Use post card on last page.



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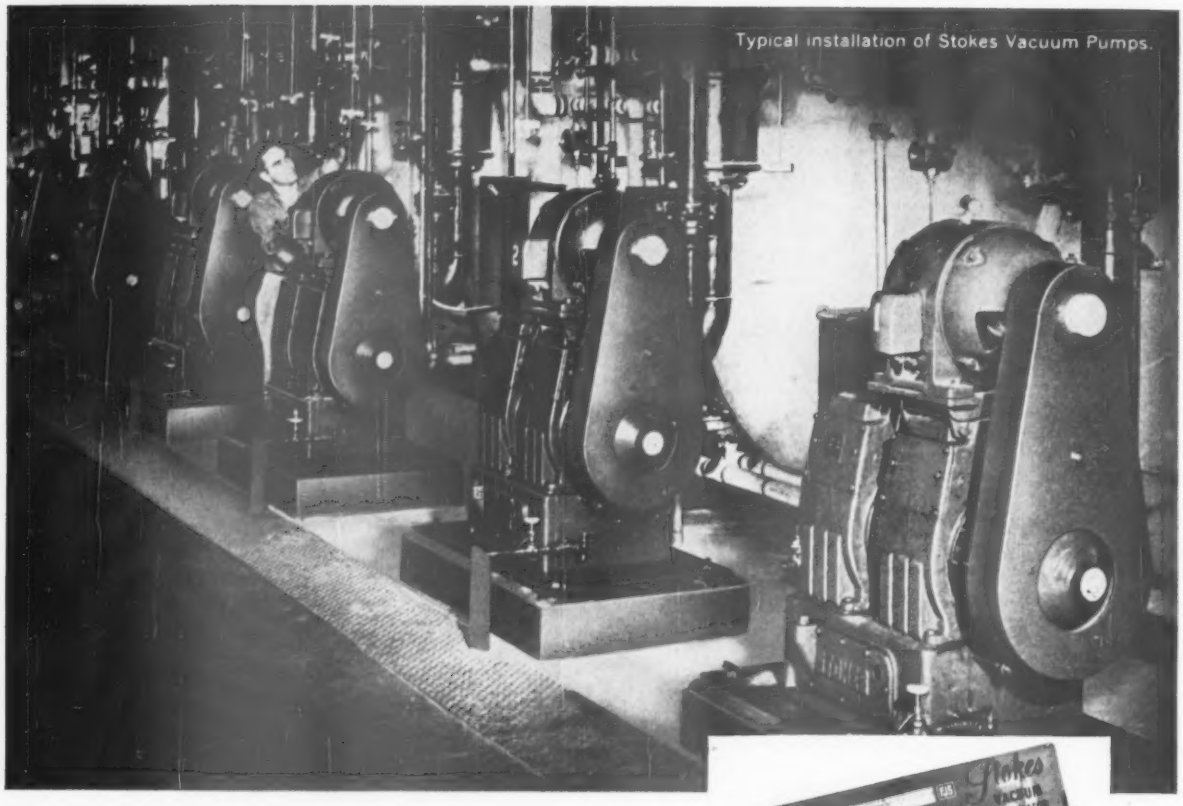
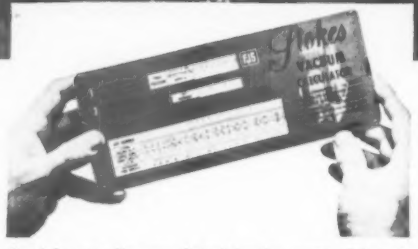


Typical installation of Stokes Vacuum Pumps.

Stokes Microvac Pumps... basic to Vacuum Processing



Send for new Vacuum Calculator for rapid slide-rule calculations. Includes standard ABCD log scale. Also send for Catalog 700, "Stokes Microvac Pumps for High Vacuum," with copious reference material.

High volumetric and mechanical efficiency make these famous pumps economical and reliable units in any vacuum system.

Capacities of Stokes Microvac Pumps run from 15 to 500 cfm . . . pressures to 10 microns absolute. Power consumption is low and the top-mounted motor contributes to compact design requiring minimum floor space.

Lubrication of the four moving parts (including the exhaust valve of corrosion-resistant Teflon) is fully automatic. There are no stuffing-boxes or grease-fittings, and no packing.

Parts are precision-finished, standard and interchangeable. Freedom from wear assures years of trouble-proof service.

Stokes is the only manufacturer of equipment for complete vacuum systems, including Microvac mechanical pumps, oil diffusion pumps, McLeod Gages and Vacuum Valves.

Consult with Stokes on the application of high vacuum to vacuum melting, casting, sintering, heat-treating, and de-gassing; to vacuum metallizing, gaseous diffusion, emission equipment and to other purposes for which vacuum deserves study.

F. J. Stokes Machine Company,
Philadelphia, Pa.

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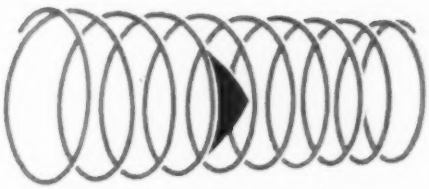
STOKES MAKES Plastics Molding Presses / Industrial Tabletting and Powder Metal Presses / Pharmaceutical Equipment / Vacuum Equipment / High Vacuum Pumps and Gages / Special Machinery

There's a 10-turn Helipot to meet your requirements



With the development of the original HELIPOT—the *first* multi-turn potentiometer—an entirely new principle of potentiometer design was introduced to the electronic industry. It made possible variable resistors combining high resolution and high precision in panel space no greater than that required for conventional single-turn potentiometers.

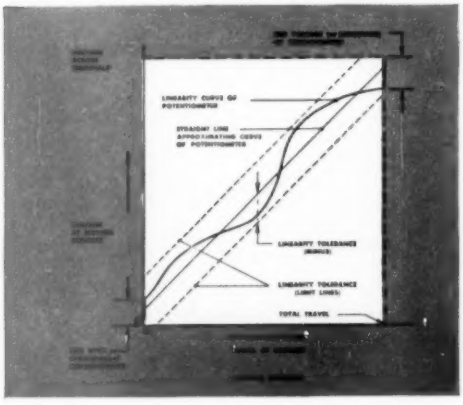
The Helipot Principle... *High resolution and precision settings require a long slide wire. But by coiling a resistance element into a helix, it is possible to gain desired resolution and precision without wasting panel space. This principle is applied in various Helipot models with slide wires ranging from 3 to 40 helical turns.*

Advantages are immediately apparent. In the case of the widely-used 10-turn Model A Helipot, for example, a 45" long slide wire—coiled into ten helical turns—is fitted into a case 1¾" in diameter, and 2" in length. Another advantage of the 10-turn pot is that, when equipped with a turns-indicating RA Precision DUODIAL, slider position can be read directly as a decimal, or percentage, of total coil length traversed.

10-TURN HELIPOT MODELS—CONDENSED SPECIFICATIONS

	Model A	Model AN	Model AJ
No. of turns	10	10	10
Resistance Range	10 ohms to 300,000 ohms	100 ohms to 250,000 ohms	100 ohms to 50,000 ohms
Resistance Tolerance: Standard	±5%	±5%	±5%
Best	±1%	±1%	±3%
*Linearity Tolerance: Standard	±0.5%	±0.5%	±0.5%
Best	±0.05% (1K ohms and above)	±0.025% (5K ohms and above)	±0.1% (above 5K ohms)
Power rating @ 40°C	5 watts	5 watts	2 watts
Mechanical Rotation	3600° +4° −0°	3600° +1° −0°	3600° +12° −0°
Electrical Rotation	3600° +4° −0°	3600° +1° −0°	3600° +12° −0°
Starting Torque	2 oz. in.	1.0±.3 oz. in.	.75 oz. in.
Running Torque	1.5 oz. in.	0.6±.3 oz. in.	.60 oz. in.
Net Weight	4 oz.	4 oz.	1 oz.

*i.e. INDEPENDENT LINEARITY. The above linearity tolerances are based on the following definition recently proposed to clarify and standardize nomenclature related to precision variable resistors. . . . "Independent linearity is the maximum deviation in percent of the total electrical output of the actual electrical output at any point from the best straight line drawn through the output versus rotation curve. (This line shall be measured through the extent of the effective electrical angle.) The slope and position of the straight line from which the linearity deviations are measured must be so adjusted as to minimize these deviations."



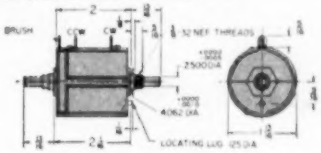
10-Turn Helipot Highlights

From the basic Helipot principle, model variations have been developed to meet new requirements:

Model A Helipot

the original 10-turn Helipot—provides a resolution from 12 to 14 times that of conventional single-turn potentiometers of same diameter (1¾"), linearities as close as ±0.05% in resistances as low as 1K ohms.

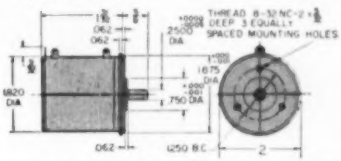
The same multi-turn principle is also available in 3 turn units (Model C), and larger-diameter units of 15 turns (Model B), 25 turns (Model D), and 40 turns (Model E)—a type for every application from 5 ohms to 1 megohm.



Model AN Helipot

an ultra-precision version of the basic 10-turn Helipot. Produced in volume to extremely close electrical and mechanical tolerances, this unit features precision ball bearings (Class 5), servo mounting lid, plus linearity tolerance as close as ±0.025% as low as 5K. A 3-turn unit (Model CN) is also available.

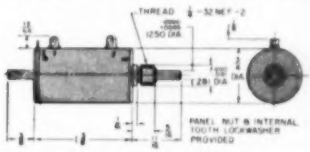
Models AN and CN are particularly recommended for precise servo-mechanism applications and represent the most advanced design and highest quality available today in the field of precision potentiometers.



Model AJ Helipot

a 10-turn *miniature* Helipot only ¾" in diameter, weighs 1 oz., has slide wire 18" long. Also available with servo mounting (Model AJS) and servo mounting with *ball* bearings (Model AJSP). Linearities as close as ±0.1% as low as 5K.

Designed for long life under severe operating conditions, the AJ Series is widely used where small size and weight are vital.



Design details on above units are subject to change without notice. Certified drawings available upon request.

Only Helipot is able to supply—in volume—multi-turn helical potentiometers *with special features to meet your particular needs* . . . Special Shafts, Extra Spot Welded Taps at any position, Ganged Assemblies (except AJ), Special Temperature Coefficients, etc. Send us your requirements!

For complete details contact your nearby Helipot representative. Or write direct.

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When Space is at a Premium and Performance is Essential . . .

THESE RESISTORS DO THE TRICK!

Cramped by small space and big requirements? Take a look at 8 pygmy resistors that make room for reliability anywhere. All were developed by IRC to fill specific wants. Many meet JAN or MIL Specifications. And all are available on short delivery cycles.

Smallest Fixed Composition Resistor in the World

Type BTR-⅓ watt. Meets JAN-R-11 Specifications, Filament-type resistance element, extra-Bakelite-sealed against moisture and humidity. Body less than ½" long—3/32" in diameter. Anchored, non-loosening leads. Low operating temperature and high power dissipation. Resistance change less than 1% under 5-hour vibration test. Easily meets rigorous requirements of avionic equipment. Send for full details in Data Bulletin B-1.

Small, Deposited Carbon PRECISTOR

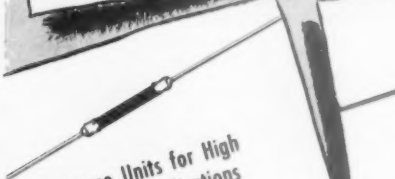
Type DCC—½, 1 and 2 watts—Combines accuracy and economy with high stability, low voltage coefficient, low capacitive and inductive reactance in high frequency applications. Resistance body size 5/16" x 5/32". Excellent for circuits where carbon compositions are unsuitable and wire wound precisions too large or expensive. Designed to meet Signal Corps Specification MIL-R-10509A. Full technical information in Data Bulletin B-7.

New Boron-Carbon PRECISTOR—Ultimate in Stable Non-Wire Wounds

Type BOC—Boron-Carbon PRECISTOR meets the most critical circuitry needs—conforms to all requirements of MIL-R-10509A. Voltage coefficient—less than 20 parts per million per volt. Load life extraordinary; on a 500-hour test at ambient temperature of 40°C. resistance change will not exceed 2%. ½ watt. Resistance body 5/16" x 5/32". Send for complete details. Data Bulletin B-6.

Most Reliable and Stable of All Precision Wire Wounds

Type WW—Far surpasses MIL-R-93A Specifications. Severe cycling and 100-hour load tests produce no change in resistance. Tests also show high mechanical strength, freedom from shorting, resistance to high humidity. New winding forms hold more wire—give higher resistance. New winding technique ends shorted turns or winding strains. New insulation assures long trouble-free life. New terminations are rugged, strain-free. Best for avionic equipment—by unbiased test. Complete data in Data Bulletin D-3.



Miniature Units for High Frequency Applications

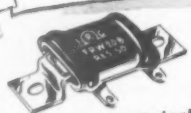
Type MPM—Active resistance section only ⅜" long—body 5/16" x .100". Thin resistance film permanently bonded to solid steatite ceramic rods. Phenolic varnish insulation. Excellent electrical characteristics—low voltage and temperature coefficients of resistance. Power rating—¼ watt at 40°C. ambient. Ask for full details in Data Bulletin F-1.

High Ohmic, High Voltage Resistors with Axial Leads

Type MVX—Body 2" long—¼" diameter. For high voltage applications where high resistance and power are needed. Helical turns of resistance coating provide long, effective resistance path. Low specific-resistance materials assure exceptional stability—even in very high values. Send for complete information in Data Bulletin G-2.

Flat Insulated Wire Wound—Most Adaptable Ever

Type MW—fixed or adjustable. Meets widest variety of design requirements. Low initial and mounting costs. Flexibility in providing taps at low cost. Offers many opportunities for saving space. Unlike most wire wounds, can be operated at full "on-plate" rating without exceeding rated temperature rise of 100°C. Practically impervious to elements. Mounting bracket transfers heat to chassis. Takes overloads of 150% indefinitely with little effect. Write for complete information in Data Bulletin B-2.



For High Wattage Dissipation—Singly or Ganged

Type FRW—Corresponds to JAN-RW-Types. Depth—½"—Lengths from 2¼". Higher space-power ratio than standard tubular wire wounds. Exceptional mechanical strength; withstands severe vibration. Can be mounted vertically or horizontally. Choice of 2 coatings—to withstand extreme heat or unusually humid atmospheres. Fixed or adjustable. Get particulars in Data Bulletin C-1.

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Ion chamber window .0002" (.66 mg/cm²) thick passes alphas down to 2 Mev and betas down to .05 Mev. Window located only 3/8" above flat surface. Ranges 0-500/2500/12,500 CPM for alphas; corresponding radium gamma ranges 0-0.7/3.5/17.5 mr/hr.

Three tube, 100% negative feedback amplifier with electrometer input has gain of 3500.

Unusual Stability

Humidity effects are degenerated. Eight-hour drift is only 10% full scale.

Rigid structural design and an improved battery box minimize transient mechanical effects.

Simplifies Monitoring

Samson's light weight (5 lbs), large 4" x 5", ion chamber window, and 6" fan meter combine to enable rapid, easy survey of contaminated surfaces.

The Raychronix Model D-5 Survey Meter, shown here with the D-5A beta-gamma probe (optional), has been redesigned to give even more reliable monitoring performance. A completely new plug-in metal battery box features screw type contacts on the long-life mercury cells — offering freedom from contact corrosion troubles.

The stainless steel bottom screen with 80% open area is now wrapped over the sides of the instrument for both rigidity and to permit taping if desired. The screen is easily removed for decontamination.

Also featured is a new sure-grip handle with flashing light to indicate when instrument is operating.

For the full details on these and other Samson features, why not send today for the Samson technical bulletin and full Raychronix catalog. No obligation, of course.

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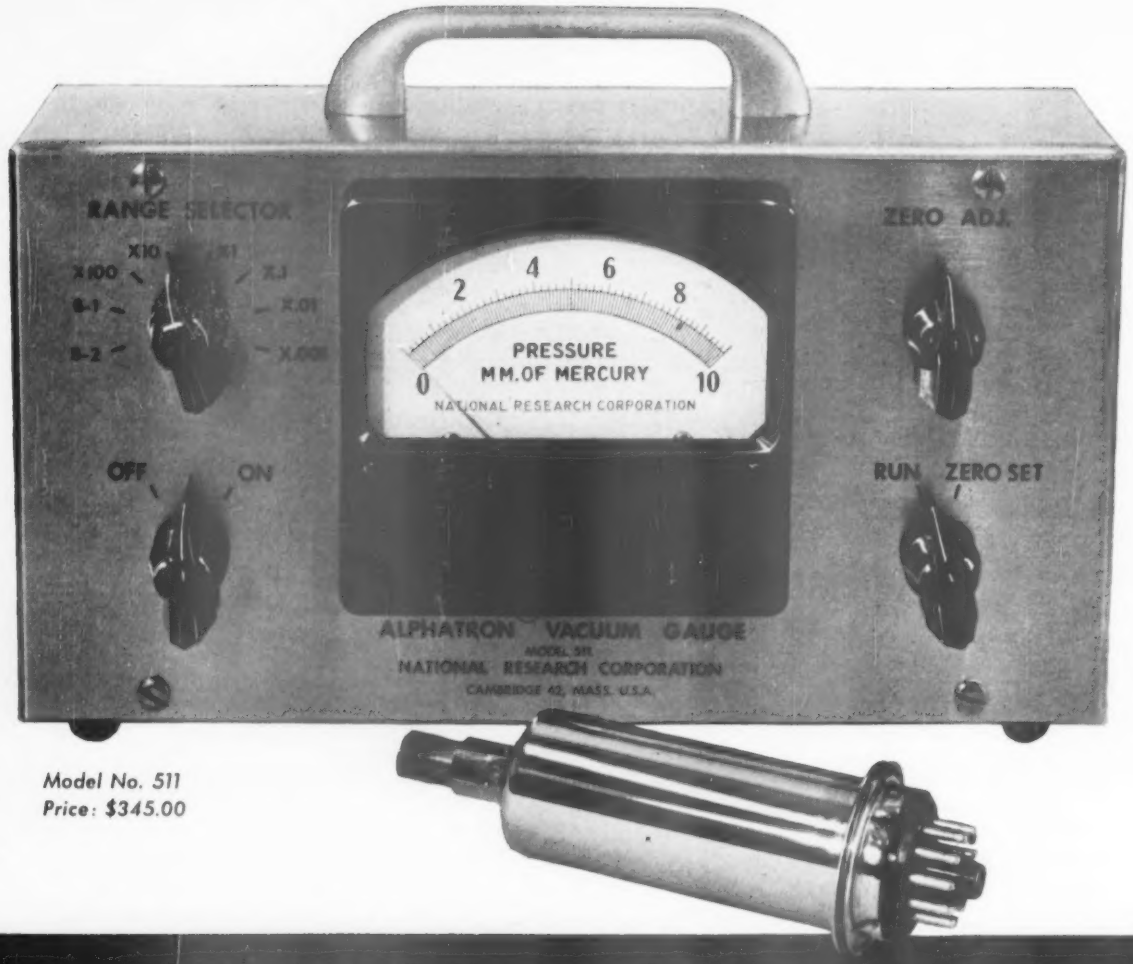

Model No. 511
Price: $345.00

Versatile New Alphatron* VACUUM GAUGE...

NEW LOW COST—WIDER RANGE

BATTERY OPERATION eliminates expensive power supply, improves accuracy and stability by removing variables of line voltage and power supply.

1000 TO 0.0001 mm HG READINGS. Wider range than previous models. Full scale deflections at 1000, 100, 10, 1, 0.1 and .01 mm HG absolute. All scales linear.

QUICK START. Only a few seconds warm-up time required. Convenient "on-off" operation saves batteries. Special switch permits instant check of battery condition on meter.

PERMANENT ACCURACY of ± 2% full scale. Long half-life ionization source insures permanent maintenance of original factory calibration.

INSTANT RESPONSE. Tracks pressure fluctuations with negligible time lag.

SMALL VOLUME. Net addition to your vacuum system about 50 cc.

SMALL, LIGHT, PORTABLE. As convenient to use as it is accurate and dependable. Write for more information.

*Reg. U. S. Pat. Off.

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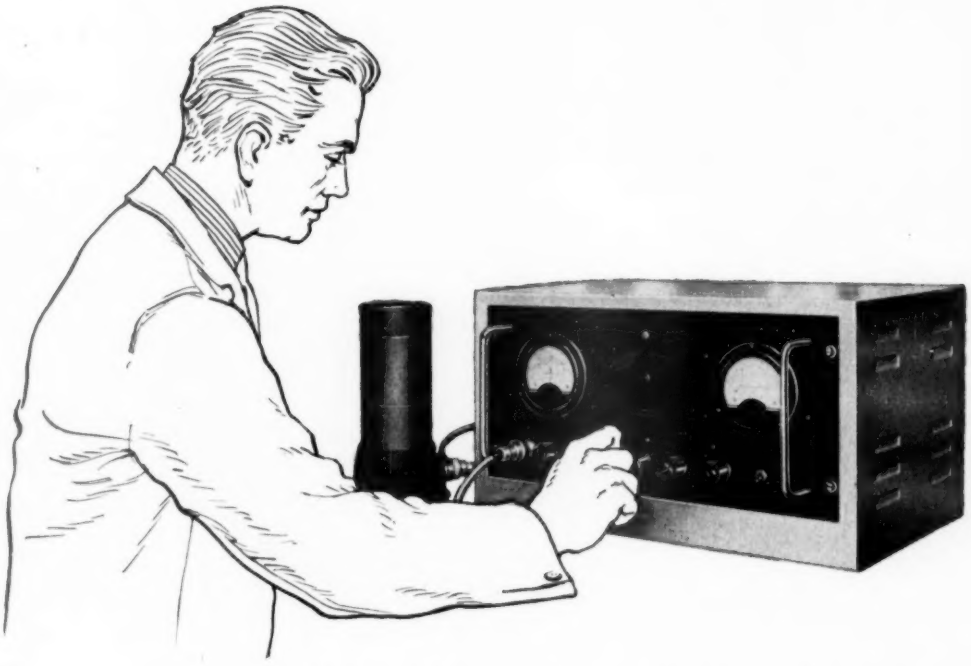
METALLURGY - HEMYDRATION DISTILLATION COATING - APPLIED PHYSICS

National Research Corporation

EQUIPMENT DIVISION

Seventy Memorial Drive, Cambridge, Massachusetts

EKCO TYPE N522 RATEMETER



This is a precision counting-rate meter incorporating an input amplifier and a built-in variable high-voltage supply. It requires only the addition of a G.M. tube or scintillation counter to form a complete counting equipment. This new instrument is a development from the Ekco type 1037 which it replaces.

SPECIFICATION

INPUTS. The unit operates from positive pulses within the range 5v to 50v. An amplifier is provided for use with G.M. tubes and has switched gains of X2, X10 and X50; this operates from negative pulses.

DISCRIMINATION AND PARALYSIS. The discriminator permits only those pulses whose amplitude exceeds the pre-set level to be counted, this level being indicated on a 3½" meter. The Ratemeter can be rendered inoperative for pre-determined periods of 5 microseconds, 200 microseconds or 5 milliseconds after receipt of a pulse.

RANGES. Eight ranges are provided giving the following full-scale rate readings:—
3, 10, 30, 100, 300, 1000, 3000, and 10,000 pulses per second.

INTEGRATION. A series of integrating time-constants is provided, extending to 80 seconds.

ACCURACY. For steady-rate counting the circuit accuracy is better than ± 1% and that of the meter is better than ± 1% above mid-scale.

HIGH-VOLTAGE SUPPLY. Two ranges, variable from 250 to 1000 volts and 500 to 2000 volts. Stability ± 0.5% for ± 10% mains variation. The maximum output current is 80 microamps up to 1500 volts decreasing to 10 microamps at 2000 volts.

EXTERNAL POWER SUPPLIES. Power is available for operating an external quench unit or Scintillation counter.

MAINS INPUT. 110-120 volts and 200-250 volts, 40-60 c/s.

EKCO ELECTRONICS

SCALING UNITS · SCINTILLATION COUNTERS · COUNTING RATEMETERS · RADIATION MONITORS · VIBRATING REED ELECTROMETERS · G.M. TUBES · LEAD SHIELDING CASTLES · LINEAR AMPLIFIERS · COMPLETE COUNTING INSTALLATIONS · ACCESSORIES

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GENERAL ELECTRIC

NUCLEONICS FEBRUARY, 1953

Jerome D. Luntz, Editor

If We Want Nuclear Power

RECENTLY EXPRESSED industrial interest in nuclear power requires an evaluation of whether the Atomic Energy Act of 1946 meets this country's present needs for atomic energy development.

When the Act was written seven years ago, the paramount concern of the legislators was that our national program fit into the framework of an international authority. Thus, it was felt necessary to vest in the federal government complete control of fissionable materials and plants capable of producing fissionable materials.

To date, it has not been possible to set up an international control program. In addition, it has been announced that Russia has produced atomic weapons.

THESE FACTS, combined with the record of safe and secure operation of Atomic Energy Commission production plants by industry, indicate that it is no longer necessary to prohibit nongovernment activity in the nuclear power field.

These are perhaps negative reasons why the statutory limitation on industrial ownership of power reactors should be revised. On the positive side is the need we have to develop nuclear power.

There appears to be fairly common agreement that within the next 25–50 years there will be the need for a significant new source of low-cost energy. Our present energy resources will not be able to keep up with the energy needs of a growing population and a growing industrial economy.

Specifically, by the end of this century, the energy consumption of the whole world will be about 100×10^{18} BTU per century. World energy reserves (coal and oil), economically recoverable at substantially present costs, add up to $30–40 \times 10^{18}$ BTU.

The need is apparent. Can nuclear power step into the breach? This depends upon whether tough engineering problems can be licked and whether costs can be brought down low enough.

But we are not yet at a point where we can find out—mainly because there is no known nuclear power plant operating in the world today.

IN THE PAST SIX YEARS, the AEC has concentrated on military reactors (either for the production of plutonium or for the propulsion of craft). And it does not appear that the Commission intends to spend any significant sums of money on civilian nuclear power in the next several years.

But within the past year, industry has shown very great interest in pressing the development of nuclear power. The positions of three industrial groups can be summarized as follows:

One is proceeding to attack the technical problems before it decides to go ahead and finance the building of a full-scale plant. A change in the Atomic Energy Act would be necessary for the latter.

A second has proposed a joint study with AEC of technical problems. If these can be licked and AEC would guarantee it a plutonium market, it would finance a full-scale plant. A change in the Act would again be necessary.

A third wants AEC to pay for the reactor. It would pay for the generating equipment. No change in the Act would be necessary.

It is apparent that there is no agreement as to which approach should be followed. It is also clear that if the Act were changed today industry would not invest large sums tomorrow.

We don't know exactly when industry will be ready to finance full-scale plants (probably within five years). But, if we are to have nuclear power reasonably soon, it is important that in the meantime it be made clear that the Act will impose no barrier.

It is in the public interest to see that the $10-billion being spent on atomic energy results in material benefits to the public. It must be possible for nuclear power development to proceed as rapidly as possible.

Dual-Purpose Reactors:

First Step in Industrial Nuclear Power Development

About three-quarters of the costs of a power-only reactor of the future would be the same as those of power-plus-Pu reactors of today. Dual-purpose plants—with 5–7 year Pu market guarantee—would yield invaluable know-how

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INDUSTRIAL PRODUCTION of nuclear power at a price competitive with power from other sources is possible within the next few years.

Design of such a plant could begin immediately and could be followed by full-scale construction *if:*

- the design passes all operational and safety testing;
- additional plutonium-producing facilities are needed to meet the government's demand;
- necessary changes in the Atomic Energy Act are made.

Under an agreement with the Atomic Energy Commission, we have been studying during the last year and a half the feasibility of private industry's constructing and operating a nuclear reactor to produce both plutonium and electric power. According to the AEC, "One of the major objectives of the Commission's reactor program is the creation of a large-scale reactor to produce fissionable materials and power as joint products." (From our letter agreement with AEC.)

As a part of our study, a variety of reactor types have been considered. As a result, in the light of what is known today, it appears that a dual-purpose reactor can probably be built without waiting for substantial advances in technology.

Also we believe that such a reactor may meet the requirement of producing the power and plutonium so that the cost of each is equal to, or less than, the cost of producing them in any other way. Taxpayers would get the cheapest possible plutonium, and the electric power end of the plant would stand on its own feet without subsidy from any source.

As one way to get started, Monsanto Chemical Company and the Union Electric Company of Missouri have proposed a four-point program to the AEC. The four points are:

1. Construction and operation of an engineering mock-up
2. Design of a full-scale plant
3. A joint research and development program
4. A cooperative study of legal and administrative problems.

Upon the completion of this four-point program, we should then know whether we can proceed with private financing of a full-scale plant. Meanwhile, costs should be appropriately divided between the AEC and us. It is expected that over-all costs would be less than $5-million.

This program should be followed by a five to seven year agreement on the part of the AEC to purchase plutonium at a competitive price.

Mock-up

The first object of the program is to determine whether the reactor actually will work as planned. This means constructing and operating a pilot plant or, at least, a mock-up of components. What we are proposing has never been done. Every design and idea must be checked. Design of a completely workable plant cannot be done on paper alone without testing each operation.

We feel that it would be unnecessary actually to produce small amounts of plutonium or power in a pilot plant. This would be expensive and time consuming. The important tests can be made without splitting atoms. Parts of the engineering mock-up would be full scale but without the inconvenience of the presence of radioactivity.

The proposal does not include a complete pilot plant program as considered in the chemical industry. A true pilot plant would produce small quantities of plutonium and would involve elaborate security and safety precautions which accompany any atomic project. This would include a remote

site, shielding against dangerous radiation, and the duplication of usual services needed for any operating establishment.

The mock-up could be built anywhere because it would not involve any of these extras. Work could begin and progress much faster because it would be unnecessary to delay until suitable property could be found and necessary service buildings erected.

Full-Scale Design

Prior to building the mock-up, engineering design of the final full-scale plant must commence. Without the design to go by, the individual components could not be built. Then, as they are tested, they can, if necessary, be changed. In other words, the full-scale design and the testing of the mock-up must go hand in hand. In this way, the mechanical features of the large plant can be evaluated on a pilot plant basis. Changes, if necessary, can be made on this small scale so that a practical design for the large plant can be evolved rapidly and effectively.

Research and Development

The third point proposed is a joint research and development program. Here, certain laboratory tests are needed to obtain data on the operation and maintenance of the reactor. For example, a liquid metal must be used as a coolant instead of water. This would involve a metal such as sodium, and its possible chemical reactions with other materials in the reactor must be fully understood. The design will have to be adapted to the problems which such interactions may present. Although a great deal of work on this general subject has already been carried out within AEC laboratories, there are other questions which must be resolved as the design and test program progresses.

Another problem to be solved involves the performance of the uranium fuel elements. The method of operation and the power level of the reactor will depend in part upon this performance. To produce the cheapest plutonium, high power levels are needed so that a maximum amount of heat can flow from the element to the coolant. Also, when plutonium becomes less in demand, it may be desirable to operate the reactor for "power only." In this case, the plutonium would not be separated but would be retained as fuel. To do this, the fuel elements must be in the reactor a long time. Special tests are needed to determine the length of time the slugs can remain under the intense irradiation without becoming distorted in shape, or losing heat conductivity, or otherwise becoming unsuitable for further use.

Still another problem is the safety of the reactor and the selection of an appropriate site. The possibility of some failure of components leading to overheating either for nuclear or chemical reasons must be determined as well as the hazard which might result. To locate the reactor in an out-of-the-way place would indeed be a serious restriction for private industry. The cost of a large exclusion area equivalent to a Hanford or Savannah River location might well be prohibitive, and it is doubtful that private industry could assume the financial risks and liabilities which such an area implies. However, we believe that through our proposal ways can be found to make this type of reactor so safe that such an exclusion area would be unnecessary.

TABLE 1—Power Costs from Various Sources (6% Return after 52% Taxes)

	5,000 kw nuclear power only (15 yr. amort., 50% utiliz.)	*5,000 kw diesel plant (15 yr. amort., 50% utiliz.)*	*100,000–200,000 kw nuclear power only (20 yr. amort., 85.5% utiliz.)*	*100,000–200,000 kw dual purpose with Pu sale (5 yr. amort., 85.5% utiliz.)*	*100,000–200,000 kw standard coal fired plant (33 yr. amort., 85.5% utiliz.)*
Capital	$500/kw	$200/kw	$400/kw	$125/kw*	$170/kw
Amortization, taxes and insurance	mills/kwh 9.7	mills/kwh 3.9	mills/kwh 3.8	mills/kwh 3.6	mills/kwh 1.15
Fuel	10.0	8.0†	1.4–4.4	0.0	2.20‡
Operating	3.8	3.8	1.00	0.50	0.50
Profit and income taxes	14.2	5.7	6.7	2.10	2.80
Total mills/kwh	37.7	21.4	12.9–15.9	6.20	6.65

* Portion chargeable to power (Costs during 5 yr. amortization period).
† Oil at 10¢/gal (70¢/million BTU) and 30% efficiency.
‡ Coal at $5/ton (23¢/million BTU) and 36% efficiency.

TABLE 2—Power Costs from Dual-Purpose Reactor
100,000–200,000 kw Electrical Capacity, 6% Return after 52% Taxes, 5-Year Amortization

	With plutonium during first 5 years	*With sale of plutonium after amortization*	*Without plutonium after amortization*
Fuel	0	0	1.0–3.5
Power plant at $125/kw (amortization, property tax, insurance)	3.6	0.30	0.50
Operation	0.50	0.50	0.50
Profit and taxes	2.10	2.10	2.80*
Total mills/kwh	6.20	2.90	4.8–7.3

* Profit and taxes arbitrarily based on equivalent coal-burning plant $170/kw.

Legal, Administrative Problems

The fourth point of the program deals with legal and administrative problems. Before private industry can proceed with its own money to construct and operate any reactor in which substantial quantities of fissionable material are made, certain changes in the Atomic Energy Act are needed. For example, the present law prohibits private ownership of any facilities which produce substantial quan-

tities of fissionable material such as plutonium.

Instead of waiting to study these needed changes until construction might begin, time can be saved by approaching all problems concurrently. We propose, therefore, that joint study of the legal and associated administrative problems proceed at once so that they may perhaps be solved by the time the design, testing, and research phase is complete.

The major problems are in the field of patent rights as well as the question of private ownership of reactors which produce fissionable materials. If the reactor cannot be legally owned by a private company, it would be difficult to raise private capital for it. Also, if there is modification of the present policy which forbids the granting of patents for any invention or discovery which is useful solely in the production or utilization of fissionable material, it will be easier to get the capital needed.

The adoption of the present patent rule is understandable for times when almost all inventions in the atomic energy field were obtained at government expense. But now that major industrial participation in the reactor field is needed, and at hand, a review of this policy is in order. There should be some protection for the inventions and other original ideas developed by a company which has at its own expense and effort done further research and development work on nuclear reactors.

Another administrative problem involves government regulations pertaining to security and public safety. In this case, however, the matter is clear. These regulations must continue to be the primary responsibility of the AEC as presently required by the Atomic Energy Act. Monsanto and Union Electric have recognized from the outset that paramount security and safety requirements must remain where the Congress has put them. Private industry can aid in continuing to maintain high standards of safety and security. All plans for future operations have been made with this in mind.

Still another administrative matter is the availability of classified information about reactors. Ever since creation of the Manhattan District, the government has been, and properly so, the exclusive repository of a large segment of important atomic energy information. Control by the AEC of those segments of reactor technology which still have to be kept secret must, of course, continue. But, for industrial participation in the field, access to pertinent information by cleared personnel must continue to be permitted.

In this connection, the AEC has been most cooperative in supplying the Monsanto-Union Electric security-cleared study team with all needed information, thus permitting full utilization of the research and development work which has thus far been conducted.

Plutonium Cost

Before proposing the four-point program, preliminary estimates of the cost of plutonium production in a dual-purpose reactor of this kind were made and compared with the cost in present-day reactors designed to produce plutonium only.

Quite without regard to power production, it turns out that the liquid-metal cooling represents, in itself, an advance in technology which promises a reduction in costs.

Because of the high cost of plutonium, the reactor should be designed and operated so as to produce it as cheaply as possible regardless of the effect on the efficiency of the power production. It turns out, however, that one of the big advantages of liquid-metal cooling is that, after plutonium production has been optimized, it is still practical to generate power. It is in this sense that the two products are economically compatible.

Unless some still cheaper method is found first, present-day government plants would serve as the basis for determining the competitive price of plutonium. In comparing government costs with private industry, the same bookkeeping methods would have to be used along with the same tax computations and depreciation periods.

To determine the cost of the power separately from the plutonium depends upon a fair and proper allocation of total charges so that the more expensive plutonium is in no way being charged for power production.

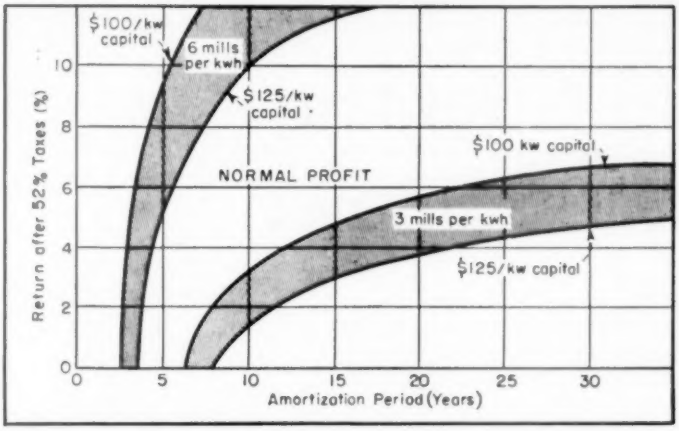
Except for fuel and operating costs, the charges depend upon capital investment. The operating costs are small, and the fuel is chargeable to plutonium. The major question, therefore, is the allocation of capital costs to the power-producing end of the plant. To answer this question, the problem of producing electric power is temporarily ignored, and the cost of cooling the plutonium-producing fuel elements in the cheapest possible way is considered.

The difference in cost between a reactor which only produces plutonium and one designed to produce electric power also is the amount which may be justifiably allocated to power generation without either penalty or credit to plutonium costs. When this subtraction is made, the answer comes out between $100 and $125 per kw of installed generating capacity. This may be compared with the cost of building large modern coal-burning plants—$175 to $200 per kw.

So far as capital costs are concerned, this gives nuclear power in a dual-purpose plant a real advantage over a standard coal-burning plant. With free heat, the result would be cheap power indeed if it were possible to amortize the nuclear power plant over the same long period of time which is customary for conventional coal-burning plants. In other words, if the capital for the nuclear power plant could be written off over a period of 30 to 35 years, we could then talk about three to four mill power as shown in the figure at right. Because of uncertainties in the nuclear power business, however, it is obviously desirable to return the invested capital as quickly as possible. For power sold at a competitive rate—say, about 6 mills per kwh—the plant could be written off in about five years and still provide 6% return after taxes.

For competitive power, about five years appears to be the minimum period which the reactor would have to operate to be economically feasible. So far as plutonium is concerned, this five-year amortization period is consistent with the government procedure of giving certificates of necessity to contractors where the product is in the interest of national defense. A certificate of necessity permits five-year depreciation for taxation purposes.

Also, in planning the four-point proposal, consideration was given to the cost of producing nuclear power as a single product without income from plutonium production. According to our studies, this is not yet economically feasible. With electricity selling at prevailing prices, the income would be



EFFECT OF AMORTIZATION PERIOD on rate of return on power production capital, based on the assumption that power production is to pay its own way

insufficient to return the investment in a reasonable time and to pay operating costs. Even where small amounts of power may be sold at high prices in certain areas, a diesel plant would still be cheaper than a nuclear power plant.

For example, it may be that a small nuclear power plant capable of producing only about 5,000 kw could be built for as little as $500 per kw with present technology. When financed to yield 6% return after taxes, the power would cost 3 to 4¢ per kwh operating at 50% capacity. As shown in Table 1, however, the same power could be provided by a diesel electric plant with an investment of about $200 per kw. This plant could produce power for only a little more than 2¢ per kwh.

The 3–4¢ figure can be immediately reduced by building a larger plant, but then it would have to compete with a modern coal-burning plant. If the installed capacity were 100,000 to 200,000 kw, capital costs for the nuclear power plant might be only $400 per kw, and the power could then be sold for as little as 13 to 16 mills depending upon the fuel "burn-up." Even this price is far from competitive today.

As the technology advances further, this cost should drop. But to accomplish this, ways must be found not only to reduce the capital but also to manufacture larger amounts of plutonium in relation to the fuel consumed.

Dual-Purpose Reactors a Step

When power breeder reactors can be built, fuel costs will be almost zero. Then the big problem which still may remain will be how to get capital costs low enough.

In principle, this more advanced reactor type would be a dual-purpose reactor since it also would produce both power and plutonium. It is for this reason that the reactor which we propose to design represents a big step forward. At present, the fuel elements would, as a practical matter, simply be irradiated. They would then be returned to the government for chemical separation of the plutonium.

When the breeder reactor becomes possible, plutonium may either be consumed as fuel or sold depending upon its value. Since a breeder is really a dual-purpose type of reactor, the dual-purpose reactor of today is a real prototype of the "power only" reactor of tomorrow. Experience with this first step would point the way to the capital cost reductions which will permit eventual production of competitive nuclear power.

While the future reactor details can only be guessed at, it is probable that internal features (such as critical assembly, controls, and some of the materials) may be quite different from those in the presently conceived dual-purpose type. But it is reasonable to estimate that about three-fourths of the cost of the future power breeder will be for items that will either be duplicated or derived from the presently conceived dual-purpose reactor.

As examples of these items, it is probable that liquid metals still will be used in both cases to remove the heat. Experience will be gained on pump design and performance, corrosion between the liquid metals and their various containers, and methods of decontaminating and purifying the liquid. Also, the heat exchanger may be very similar. Since this is a major cost item, experience in this area will be especially valuable. The proposed loading and unloading systems may well be applicable to the early power breeders. Finally, there are a variety of operating problems, including safety, decontamination, security, and radioactive waste disposal, on which any additional know-how should be a definite step toward more advanced types, whatever they turn out to be.

Before making the four-point proposal, consideration also was given to the method of operating the dual-purpose reactor as presently conceived after the investment has been paid off. Should the demand for plutonium continue, it will then be possible to produce it at a far lower price and taxpayers will benefit accordingly. As shown in Table 2, the cost of power also would drop. Power might then be 3 mills or less so that income from the sale of power could be credited to the plutonium, thereby reducing its price even further.

On the other hand, if the plutonium demand has dropped to the point where it is not worthwhile to sell it, the reactor and power-plant combination probably could be operated economically on a "power only" basis. The power cost would likely be in the 4–7 mills per kwh range, depending again on how long the fuel elements could be left in the reactor. An important advantage of this reactor would be its standby potential in case national defense again required plutonium.

Conclusion

If there is today a continuing demand for plutonium, the dual-purpose plant is the next major step in power reactor development. We already know that production of nuclear power is technically possible, but the problem of gaining industrial participation, with economically sound financing, has not been solved. The dual-purpose reactor provides a possible solution to this problem and also would be a major advance in reactor technology. For both reasons this program should provide as much push toward the more advanced power breeders as anything that can be done today.

Absolute Beta Counting of Thick Planar Samples

On the basis of previous work and new data, several methods are presented for determining disintegration rates of thick beta-active samples to better than 20% accuracy. With the equations derived, self-scatter and self-absorption corrections can be made for samples thicker than ⅙ of the beta-ray range

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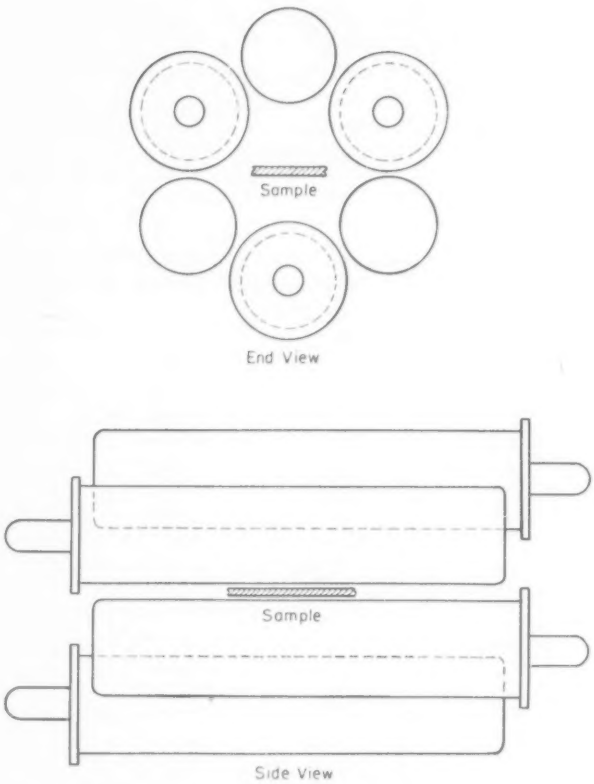

FIG. 1. Arrangement of cylindrical counters for 4π geometry

ABSOLUTE BETA COUNTING in end-on geometry of thick samples involves corrections for self-scattering and self-absorption. Though several facets of the problem have been separately investigated (*1*, *2*, *3*), theoretical treatments have been unsuccessful. This article will present an over-all experimental approach and suggest several methods for obtaining relatively accurate results.

Zumwalt (*4*) particularly, among others (*5*, *6*, *7*), has examined the factors which enter into the absolute beta counting of weightless point sources of high specific activity. According to him, the detected counts per minute, cpm, is related to the actual disintegrations per minute of the sample, dpm, by

$$(\text{cpm}) = (\text{dpm})Gf_W f_A f_B f_H f_S \quad (1)$$

where G is the solid-angle geometry of the source and counter; f_W, f_A, f_B and f_H account for the influence of the counter window, back-scattering, etc., and f_S accounts for self-absorption and self-scattering of the source. It is usually assumed that $f_S = 1$ for the thin sources used.

With samples of finite mass, it is very difficult to study self-absorption and self-scatter separately. To reduce the effects of self-scatter, self-absorption is best studied in a 4π geometry. For small sample thicknesses, back-scattering often masks self-scattering and leads to self-absorption curves which are strongly dependent on the Z of the back-scatterer (*8*). In our work, back-scattering was kept to a minimum by nylon-film sample supports of 1-mg/cm² thickness.

Self-Absorption

One method of studying self-absorption is through the use of external absorbers. Foils of inactive material of various thicknesses are interposed between the radioactive sample and the detector. The shape of the absorp-

tion curve depends to some extent on the relative positions of the sample, the absorber, and the detector (*9, 10, 11*).

However, assuming a linear relationship of the logarithm of transmitted intensity (ln I) versus absorber thickness (x), then

$$I = I_0 e^{-kx} \qquad (2)$$

where the mass absorption coefficient, k, is measured in cm²/mg, and the absorber thickness, x, in mg/cm². In a small-angle geometry ($G \leq 4\pi$), the shape of the initial portion of the curve is particularly sensitive to the experimental arrangement. It will be shown later that the disturbing influence is scattering.

Two methods are commonly used for measuring self-absorption without the aid of external absorbers. The first consists of precipitating an aliquot of activity with various amounts of inactive carrier on a defined area to form pill-shaped samples (*12, 13*). The disintegration rates of the samples are then equal and the observed activities are a function of sample thickness only.

The other method is to use various thicknesses of uniformly activated material. A measurement of the counting rate in a fixed geometry divided by the sample thickness gives the observed specific activity as a function of thickness.

Present investigation. Our work is based on measurements with sources obtained by simultaneously irradiating samples of the same area and different thickness in our betatron beam. Self-shielding is considered negligible for the thicknesses used.

A good sampling of 4π geometry is provided by an array of cylindrical counting tubes shown in Fig. 1. The G-M tubes are matched for operating voltage and are connected in parallel so that a particle entering any tube initiates a counting pulse. The samples are located on the axis of the arrangement and supported by a nylon film stretched on a Lucite framework.

The activities studied with this arrangement are produced by photoneutron reactions in the betatron beam. Though these are all positron emitters, no great difference is to be expected in their self-absorption and self-scatter behaviour from electron emitters.

Discussion. The shape of the self-absorption curve is usually well represented by an equation obtained from the assumption of exponential absorption and elimination of self-scattering. From Eq. 2, the activity from a sample of thickness x reaching a counter normal to the sample surface, $(\text{cpm})_{0,x}$, in narrow-angle geometry ($G \ll 4\pi$) is

$$(\text{cpm})_{0,x} = \frac{(\text{cpm})_0}{x}\int_0^x e^{-ky}dy = \frac{(\text{cpm})_0}{kx}(1 - e^{-kx}) \qquad (3)$$

where $(\text{cpm})_0$ is the activity which would be observed if there were no self-absorption.

If the activity is measured in a direction making an angle θ with the normal to the plane source, then the effective sample thickness is $x/\cos\theta$, and the counting rate is

$$(\text{cpm})_{\theta,x} = (\text{cpm})_0(\cos\theta/kx)(1 - e^{-kx/\cos\theta}) \qquad (4)$$

This equation represents quite well the angular distribution of beta rays from thick sources, as will be shown later. It does not, however, represent the distribution too well at intermediate sample thicknesses. For this reason, measurements of the counting rate in large-angle geometry are not well represented by the equation obtained from the integration of Eq. 4 over the angle involved, e.g. Θ

$$(\text{cpm})_{\Theta,x} = \int_0^{\Theta} \frac{(\text{cpm})_{\theta,x}}{G} 2\pi \sin\theta d\theta \qquad (5)$$

where $(\text{cpm})_{\theta,x}/G$ is the counting rate per unit solid angle at angle θ, and x is the sample thickness.

For large thicknesses, the self-absorption curves of Eqs. 3 and 5 become parallel. We find that, even for 4π geometry, the data is best represented by Eq. 3 at all thicknesses, and the self-absorption coefficient so obtained agrees with that measured in narrow-angle geometry.

In the 4π geometry of our work, the specific activity does not exhibit a maximum at small sample thickness due to self-scattering (Fig. 2). A curve of the form $(1 - e^{-s})/s$ is fitted to each of these results by taking the ratio of x to s, which gives

$$(\text{cpm})_{4\pi,x}/(\text{cpm})_{4\pi,0} = \frac{1 - e^{-s}}{s}$$

The average value of s/x is the value of k for the best fit. A plot of k versus the beta-ray end-point energy on log-log paper gives a straight line (Fig. 3) which can be represented by

$$k = 0.0155 E_m^{-1.41} \text{ cm}^2/\text{mg} \qquad (6)$$

This may be compared with empirical

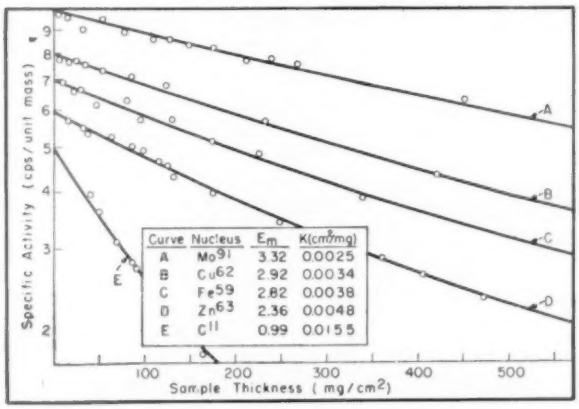

FIG. 2. Self-absorption curves taken in 4π geometry

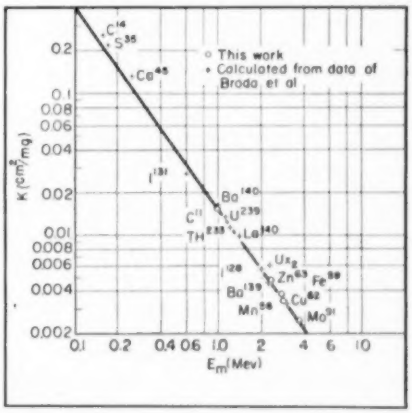

FIG. 3. Calculated absorption coefficients

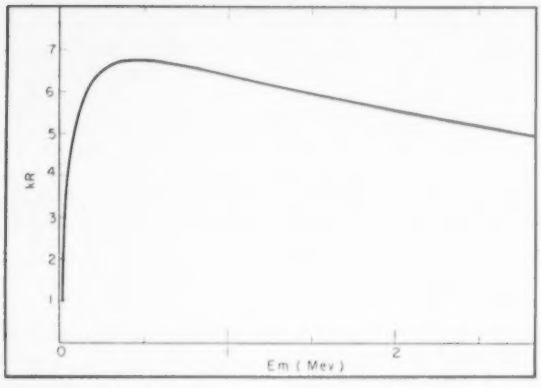

FIG. 4. Dependence of kR on beta-ray end-point energy, E_m, according to Eq. 10

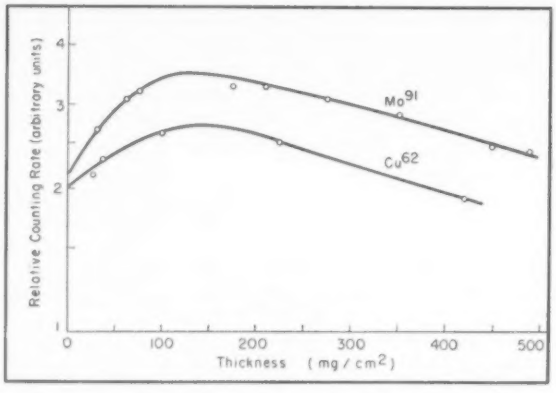

FIG. 5. Typical self-absorption curves obtained for Cu^{62} (2.92 Mev) and Mo^{91} (3.32 Mev) beta rays

relations given by Gleason (7), $k = 0.017E_m^{-1.43}$ cm²/mg, and Evans (14), $k = 0.022E_m^{-1.33}$ cm²/mg within a probable error of 0.2 Mev.

Included on Fig. 3 are values of k calculated from data given by Broda (15). The counting geometry described by Broda consists of sources disposed around the central portion of a cylindrical counter, giving essentially 2π geometry. As anticipated, his self-absorption results for electron emitters are in complete agreement with ours for positron emitters.

If the thickness of each sample is expressed in units of its beta-ray range, then the self-absorption curves are nearly identical in shape. This corresponds to replacing x in Eq. 3 by Rt, where t is the sample thickness in units of beta-ray range R. The similarity of these curves implies that kR is nearly a constant independent of the beta-ray energy E_m. Katz and Penfold (11, p. 35) have shown that exponential absorption of the beta rays implies constancy of kR.

The range of beta rays in aluminum absorbers, for beta end-point energies less than 3 Mev, is represented by (11)

$$R = 412E_m^{1.265-0.0954 \ln E_m} \text{ mg/cm}^2 \quad (7)$$

Though this expression is written for aluminum absorbers, it holds quite accurately for absorbers of any atomic number when R is expressed in mass per unit area. Combining Eqs. 6 and 7

$$kR = 6.38E_m^{-(0.1485+0.0954 \ln E_m)} \quad (8)$$

which is not very energy sensitive except at very low values of E_m. This equation is plotted in Fig. 4.

Broda (15) tested the validity of exponential absorption and determined experimental values of the external half-value absorber thickness and self-absorption half-value thickness. Letting these be respectively $\xi_{1/2}$ and $\eta_{1/2}$, then for exponential absorption we have $e^{-k\xi_{1/2}} = 0.5$, from which we find $\xi_{1/2} = 0.693/k$ and, for self-absorption, $(1 - e^{-k\eta_{1/2}})/k\eta_{1/2} = 0.5$, giving $\eta_{1/2} = 1.594/k$. Thus, the expected ratio of these half-thickness values is $\eta_{1/2}/\xi_{1/2} = 2.30$. Broda found individual experimental values of 1.8 to 2.4 with an average value of 2.2.

Self-Scattering

Self-scattering, the scattering effect of the source material, results in a beta-ray angular distribution which depends on the sample thickness. This dependence is over and above that due to self-absorption. That the angular distribution is a function of sample thickness was first pointed out by Collie, Shaw and Gale (2). Elliot, Engelkemeir and Rubinson (3) measured the angular distribution of UX_2 beta particles from plane sources of various thicknesses. They found that Eq. 8 gives a good fit at the thicknesses investigated.

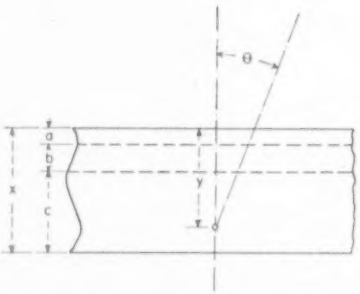

FIG. 6. Source layers effecting beta-ray distribution: (a) isotropic, (b) angular, and (c) random distribution

The most striking effect of self-scattering, and the most troublesome in absolute beta counting, occurs when a "self-absorption curve" is taken in narrow angle geometry ($G \ll 2\pi$) (16). Recent curves taken in our laboratory for high beta-ray energy are shown in Fig. 5. It has been suggested that the initial rise in the curve is due to self-scatter (16) or the interplay of self-scatter and self-absorption (2). A similar effect has been observed with external absorbers (1).

Electron scattering may account qualitatively for the maximum of Fig. 5 as follows: If an electron stream is incident on a thin foil ($x \ll R$), the stream is strongly scattered by thicknesses for which absorption is negligible (11, 17). The most probable angle of scattering increases with increasing thickness of foil traversed and approaches an angle between 25 and 30 degrees (18). At this point, the motion of the electrons prior to emergence is completely random, and additional absorbers only attenuate the beam intensity.

Sample scattering layers. A thick radioactive sample can be considered to be made of three layers, a, b and c (Fig. 6).

1. All radiation originating in the surface layer, a, ideally of zero thickness, has an isotropic distribution.

2. Electrons originating within layer b directed normally to the surface are not significantly scattered. How-

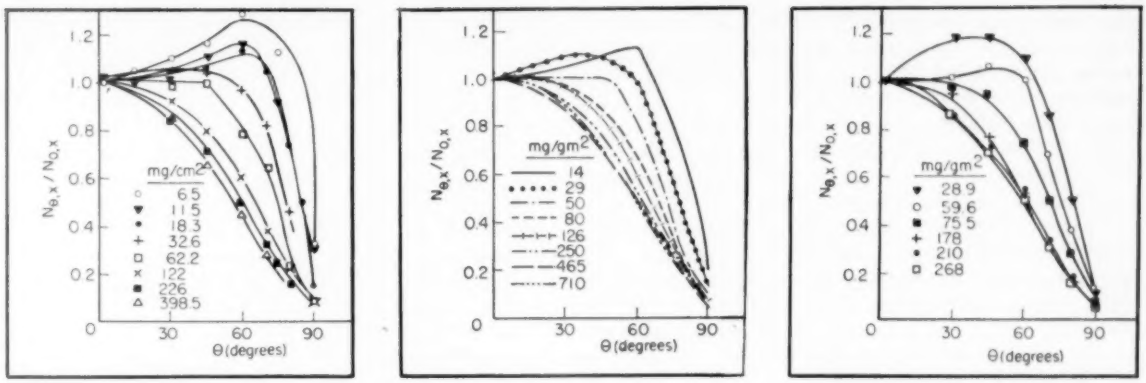

FIG. 7. Angular distribution of beta particles from irradiated copper, zinc and molybdenum foils of various thicknesses

ever, those emitted at an appreciable angle θ to this direction have the most probable angle of scattering increasing with θ. The scattering reduces the number of betas emerging at large angles, and considering the absorption in the forward direction to be negligible, the number emerging approximately normal to the surface must be correspondingly increased. Thus self-scattering in this region results in an increase in counting rate if only betas normal to the sample are detected ("forescattering" in the case of external absorbers). This has been demonstrated by Brownell (*19*) in experiments on P^{32} 1.70-Mev beta rays.

3. Due to multiple scattering, there is no preferred direction for motion of the electrons from region c, i.e., all layers $y > a + b$. It corresponds to the material in the sample below that thickness which results in complete diffusion of the electrons. Zumwalt (*4*, appendix c) has shown that the minimum depth of penetration of electrons into an absorber, before diffusion may be assumed to have set in, is given by*

$$x_d = (1 - e^{-5.9/Z})R \qquad (9)$$

It is not unreasonable to assume that $a + b \sim x_d$. From Eq. 9 it follows that for $Z > 13$ (aluminum), $a + b \sim R/4$. The number of electrons emerging from region c in any given direction is not altered by further scattering and depends solely on the thickness of absorber traversed. An electron, originating a distance y below the surface, travels a distance $y/\cos\theta$ in the direction θ before it emerges from the surface. This gives rise to a $\cos\theta$ distribution, represented by Eq. 4.

To summarize, absorption alone gives an angular distribution which goes from isotropic at $x = 0$ (layer a) to $\cos\theta$ for x large. Superposed on this we have the changing distribution from region b due to self-scattering. The most pronounced change in the distribution, from isotropic to $\cos\theta$, is expected in the region $x \sim b$. As a result of these effects, a counter subtending a solid angle less than 2π at the sample would record a greater fraction of the emerging electrons from thick samples than from thin samples.

Present investigation. We have determined the angular distribution of beta rays from samples of various thicknesses by the use of a specially constructed apparatus similar to that used by Yaffe (*20*). The center of a small planar source was maintained on the axis of the end-on counter tube and at a constant distance from the center of its window. The window was restricted by a lead iris, so that the sample could be approximated by a point source to give an accuracy for G of better than 1%. A source support consisting of a nylon film cemented to a Lucite framework could be rotated so that the normal from the counter window could intersect the sample at any desired angle.

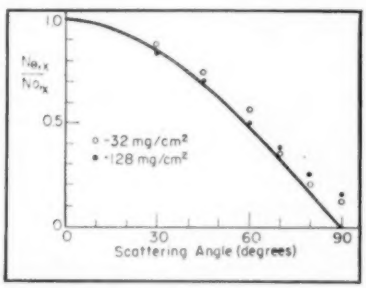

FIG. 8. Angular distribution of beta rays from zirconium metal (0.9-Mev Zr^{89})

Highly active sources are required (greater than 20 $\mu c/cm^2$ of sample area) in order that an accurate determination of the angular distribution can be made. This severely limited the number of betatron-induced activities which we could examine.

Results. The angular distribution of beta particles as a function of sample thickness for copper, zinc, and molybdenum foils, containing the photo-induced activities Cu^{62}, Zn^{63} and Mo^{91}, is shown in the curves of Fig. 7. Approximate distributions were also obtained for the following materials with somewhat lower specific activities (radioisotope in parenthesis): graphite (C^{11}), nickel foils (Ni^{57}) boric acid (O^{15}), rubidium nitrate (Rb^{86}) and zirconium foils (Zr^{89}). The curve for Zr^{89} is plotted in Fig. 8. All readings are normalized to unit counting rate normal to the sample.

The curves of Fig. 7 are almost identical in shape when sample thickness is expressed as a fraction of the range of the beta rays (R). This is demonstrated in Fig. 9 where the intensities are plotted for the three samples at 30 and 60 degrees, relative to the normal intensity. In each case,

* A better formula than these authors used for the range-energy relation (Eq. 7), valid over a wider range of energies, does not alter Eq. 9 significantly.

the points may be represented by a single curve to within experimental accuracy. A wider range of beta energies and atomic numbers for the samples will have to be covered before this simple relation is definitely established.

If $n_{\theta,x}$ is the counting rate of a sample of thickness x in the above restricted geometry at an angle θ to its normal, then the counting rate for this geometry, averaged over all angles, is

$$\bar{n}_x = \frac{1}{2\pi}\int_0^{\pi/2} n_{\theta,x} 2\pi \sin\theta d\theta \quad (10)$$

The total number of betas leaving the sample surface is then

$$N_x = \bar{n}_x(4\pi/G) \quad (11)$$

where G, the solid angle of the defined geometry, is assumed constant.

The ratio $n_{0,x}/\bar{n}_x$ is plotted in Fig. 10 for the O^{15}, Rb^{86}, and Zr^{89} samples. Again, when the sample thickness is expressed in units of R, the experimental points define a single curve. Since the atomic numbers for the three samples are not very different, the dependence on Z is not established. This dependence is not expected to be very strong for $Z \geq 13$, since it is probably related to Z through x_d defined by Eq. 9.

An examination of Fig. 10 indicates that the activity normal to the sample, $n_{0,x}$, is twice the average for samples with $x \geq 0.2R$. While this is a necessary condition for a cosine distribution, the sufficient condition is established by the curves of Figs. 8 and 9. We conclude that for these three samples, at least, the distribution remains cosine for all values of $x \geq 0.2R$. This bears out our previous discussion of Eq. 9.

Two self-absorption curves of the Zn^{63} beta rays are shown in Fig. 11. One was taken in 4π geometry and is well represented by the expression $(1 - e^{-kx})/kx$ with $k = 0.0048$ cm²/mg. The other was taken in very narrow-angle geometry, normal to the sample, and is well represented by the product of self-scattering and self-absorption curves

$$f = \frac{n_{0,x}}{\bar{n}_x}\frac{(1 - e^{-kx})}{kx} \quad (12)$$

where $n_{0,x}/\bar{n}_x$ is taken from the data of Fig. 10. Equation 12 is derived in the following way:

The total number of beta rays leaving the sample surface, N_x, is given by Eq. 11. This is related to the disintegration rate by

$$N_x = (\text{dpm})\frac{1 - e^{-kx}}{kx} \quad (13)$$

The number of beta rays leaving the sample surface and entering a cone of half angle Θ is, by Eq. 5

$$(\text{cpm})_{\Theta,x} = \int_0^{\Theta} \frac{n_{\theta,x}}{G} 2\pi \sin\theta d\theta \quad (14)$$

Now focusing our attention on the self-absorption and self-scattering correc-

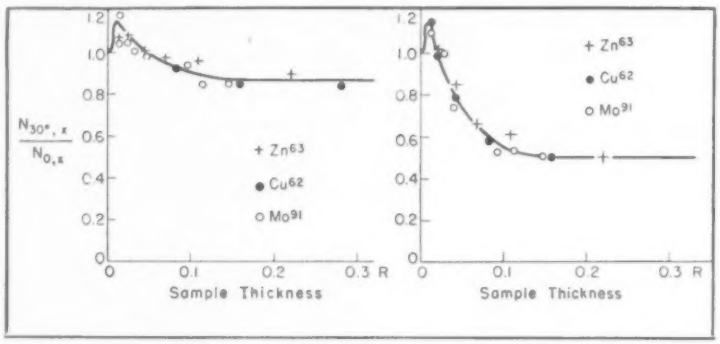

FIG. 9. Ratio of angular intensity to normal intensity vs sample thickness expressed in fractions of sample range. Values taken from Fig. 7

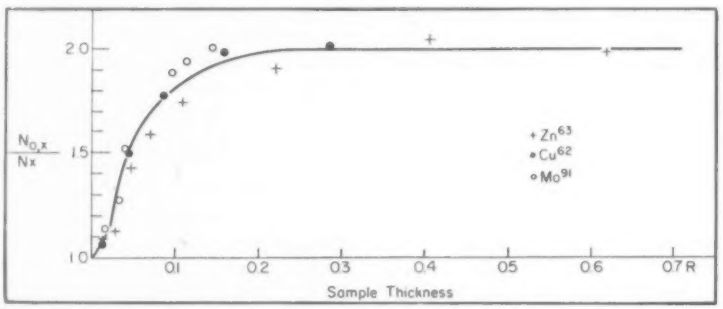

FIG. 10. Ratio of normal to average intensity as a function of sample thickness

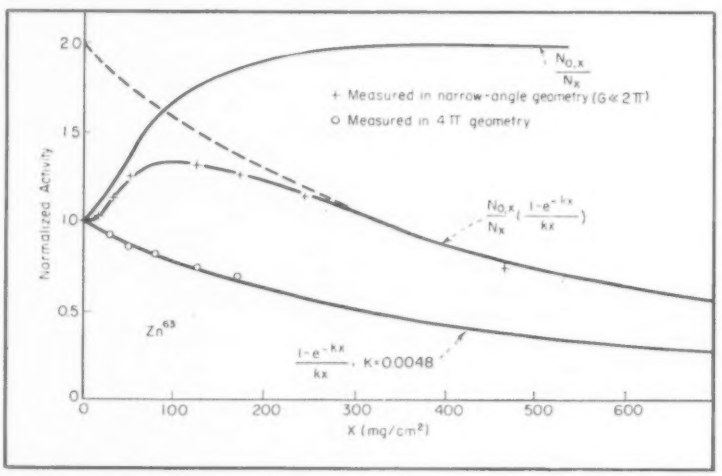

FIG. 11. Self-absorption curves for Zn^{63} beta rays taken in very narrow-angle and 4π geometry

tion factor only, we have from Eq. 1

$$(\text{cpm})_{\theta,x} = (\text{dpm})\frac{G(\Theta)}{4\pi} f_s \quad (15)$$

where $G(\Theta) = 2\pi(1 - \cos\Theta)$. Combining Eqs. 11, 13, 14 and 15

$$f_s = \frac{1}{(1-\cos\Theta)} \frac{1-e^{-kx}}{kx} \int_0^{\Theta} \left(\frac{n_{\theta,x}}{n_x}\right) \sin\theta d\theta \quad (16)$$

Angle Θ is subtended by the counter window at the sample. For $\Theta \sim 0$, this reduces to Eq. 12.

A similar experiment with Cu^{62} samples gives essentially the same results, though in this case the experimental points for the narrow-angle geometry do not fall as well on the predicted curve.

It is important to note that a self-absorption curve taken in narrow-angle geometry with thick samples gives, on simple extrapolation to zero sample thickness, an activity which is twice the specific activity from a thin sample. Such an extrapolation is indicated by the dashed curve of Fig. 11. A geometry intermediate between these two extremes results in a self-absorption curve which lies between these two limiting curves. The observed activities may again be shown to be the product of the self-absorption and self-scatter factors.

The procedure often adopted for evaluating f_s is to take a self-absorption curve in a given geometry, generally using samples thicker than $0.2R$, and to extrapolate these to zero thickness, assuming exponential absorption. With this procedure, the turnover at small sample thickness is missed, and the correction factor obtained is in error by the angular distribution effect. Since thick samples are used, $n_{\theta,x} = n_{0,x} \cos\theta$, and, from Eq. 16, the error introduced in such an extrapolation is

$$S = \frac{1}{1-\cos\Theta}\int_0^{\Theta} \cos\theta \sin\theta d\theta = \frac{\sin^2\Theta}{1-\cos\Theta} \quad (17)$$

This factor varies from unity (no error) for $\Theta = 90$ degrees, that is 2π geometry, to 2 (100% error) for $\Theta \sim 0$.

Counting Procedures

With the methods to be outlined, it is hoped that the absolute disintegration rates may be obtained to better than 20% accuracy. This is not as poor as it may seem if it is compared to the best calibration obtainable for thin samples. Putman (*21*) has recently collected data which shows discrepancies in such measurements between various laboratories of 0–12%, averaging about 5%.

1. When sufficient activity is available and with well defined narrow-angle geometry, the observed activity can be corrected for self-absorption by Eq. 3 with k from Fig. 3. Samples thicker than $0.2R$ should be used, and, since these have $\cos\theta$ distribution, the observed activity is twice the average, which requires a further correction factor of ½.

2. Samples often vary in specific activity. If a sample of high specific activity is calibrated, either by the procedure for weightless sources (*4*, *5*, *6*, *7*) or as outlined in **1**, then a sample of very low specific activity may be readily calibrated by comparison to this source.

The two samples, each thicker than $0.2R$, are counted in the same geometry. Since the $\cos\theta$ distribution holds for both samples, the same fraction of each activity is measured and, when corrected for self-absorption by Eq. 3, gives their relative specific disintegration rates. It is understood of course that the other correction factors outlined in Eq. 1 are taken into consideration.

The following equations are used for this type of standardization. Combining Eqs. 15 and 16

$$(\text{cpm})_{\theta,x} = (\text{dpm})\frac{1-e^{-kx}}{2kx} \int_0^{\Theta} \left(\frac{n_{\theta,x}}{n_x}\right) \sin\theta d\theta \quad (18)$$

When two samples, a and b, which have the same angular distribution, are compared in the same geometry, then

$$\frac{(\text{cpm})_a}{(\text{cpm})_b} = \frac{(\text{dpm})_a\left(\frac{1-e^{-kx}}{kx}\right)_a}{(\text{dpm})_b\left(\frac{1-e^{-kx}}{kx}\right)_b} \quad (19)$$

Thus, the disintegration rate of the unknown sample, a, is easily calculated from the measured counting rates and the disintegration rate of the standard sample, b.

When good self-absorption curves are available for the two sources in the given geometry, that is, down to very thin sample thicknesses, then the ratio of their absolute disintegration rates are obtained directly without recourse to Eq. 3. Each curve is normalized to the activity obtained for its sample in the comparison, and the ratio of the absolute disintegration rates is now the ratio of the normalized curves at zero sample thickness.

3. When only one thickness is available of a sample whose absolute disintegration rate is to be measured, and this thickness is less than $0.2R$, the previous two methods cannot be used. Approximate normalization can be effected against a standard such that the sample and standard have thicknesses which are the same fraction of their beta range. The correction factors (for self-absorption and self-scattering) under these circumstances are equal to a first approximation.

As an indication of the accuracy of this method, suppose the samples have a thickness of $0.1R$, and $kR = 5$ for the standard and 6.8 for the unknown; then an error of about 15% may be incurred.

* * *

The authors would like to thank the many associates in this laboratory who contributed generously of their ideas during the progress of this work. They would particularly like to acknowledge the work of Mr. R. A. Douglas who performed the initial experiments, the valuable contributions of Mr. W. Harms in some phases of the work and the invaluable discussions with Dr. R. N. H. Haslam.

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FIG. 1. Bronze inlay in iron Assyrian helmet of the 9th Century B.C. shows up in Tm^{170} radiograph to be a design of human figures and symbols not previously recognizable. Radiographed by researchers at the British Museum, helmet was not suitable for normal X-ray inspection technique because of its hollow hemispherical shape. For Tm^{170} radiograph, source was placed inside helmet, film outside

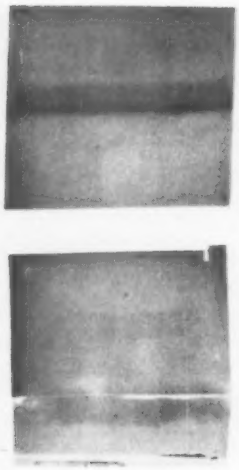

FIG. 2. Argon-arc-welded ⅜-inch sheet aluminum is subject of Tm^{170} radiographs; good weld is at top, bad weld at bottom (18-inch range, Ilford Industrial C film)

Low-Energy Gamma-Ray Sources

A search for additional gamma sources for industry, medicine, and research has led to consideration of the low-energy isotopes Tm^{170}, Am^{241}, Eu^{155}, and Xe^{133}

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SINCE research, industrial, and medical interests will continue to find applications for gamma rays in their work, it is clearly desirable that the range of suitable radioactive sources be extended.

A requirement common to a large number of the applications is a source with uncommon and often conflicting characteristics, such as long life, high source strength coupled with small source size, and near-monochromatic radiation. In addition, economic production and good availability are of importance. At present, the range of available sources most closely filling these needs may generally be given, in order of main gamma-ray energies, as Na^{24} (14.9 hr) 2.76, 1.38 Mev; radium (1,590 yr) 1.76, 1.2, 0.6 Mev; Co^{60} (5.3 yr) 1.33, 1.17 Mev; Ta^{182} (117 d) 1.2, 1.1 Mev; Ir^{192} (70 d) 0.65 to 0.14 Mev; Au^{198} (2.96 d) 0.41 Mev; and I^{131} (8 d) 0.64, 0.36, 0.28, 0.08 Mev. Na^{24}, Au^{198}, and I^{131} are limited in use by short half-life.

The purpose of this article is to describe the results of some exploratory work where the gap in this range is greatest, namely, in the low-energy field. The isotopes investigated were Tm^{170} (see radiographs in Figs. 1–3), Am^{241} (see Fig. 4), Eu^{155}, and Xe^{133}.

Thulium

Thulium-170 possesses suitable properties, as a source of soft electromagnetic quanta, for use in radiography and for measuring the thickness of materials (*1*). Mayneord (*2*) has demonstrated its application also in diagnostic radiology, by taking radiographs with a small source placed within body cavities, and has suggested it for possible use where X-ray machinery is not available.

Thulium is a rare earth of the lanthanide series, having a single stable isotope of atomic weight 169. It is available commercially in small amounts in a limited number of compounds. Its oxide was chosen as most simple and stable for the present work. A purity of 99% was found a suitable compromise with the high cost of the material [present price in the United Kingdom is £108 (about $300) per gm]. Usually, however, only less than 100 mg is needed for a source, and source life may be virtually infinite with periodic re-activation in a reactor.

It is agreed by observers that 127-day Tm^{170} decays by two beta components, one of 0.97 Mev to the ground state of stable Yb^{170}, the other of 0.886 Mev to an excited state of Yb^{170} which decays by a 0.084-Mev gamma ray (*3–7*).

Frazer (*3*) assigns to the latter decay

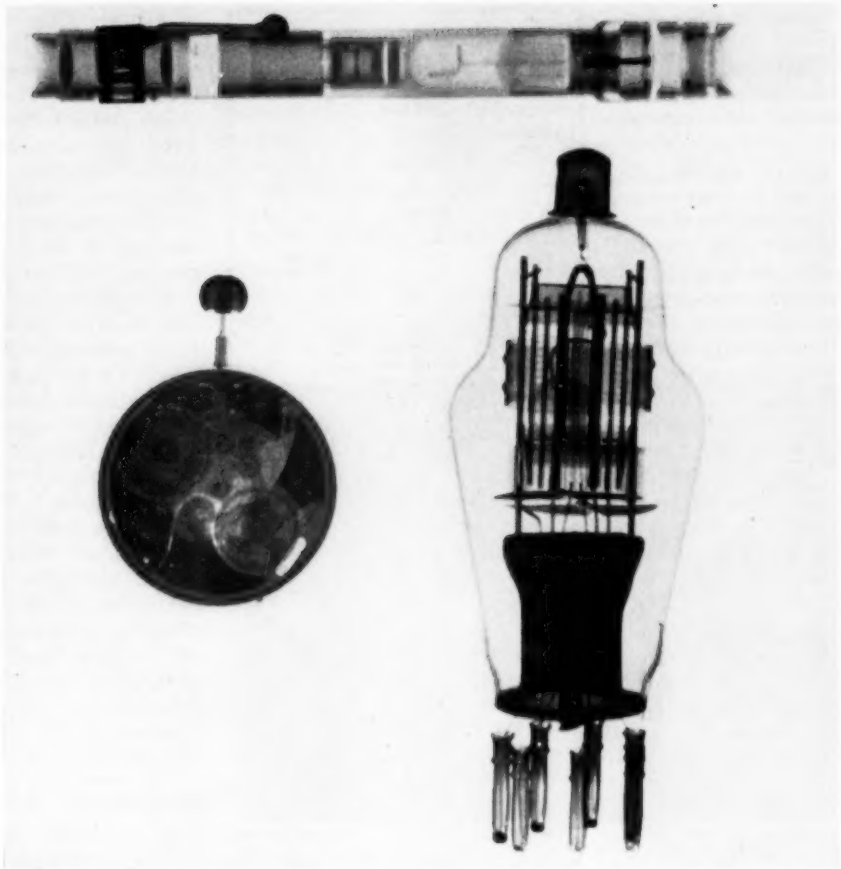

FIG. 3. Good definition of parts is seen in Tm^{170} radiograph of quartz-fiber electroscope, stopwatch, and electronic tube

branch a probability of ~10%. More recent work by Graham *et al.* (*8*), however, gives a figure of 24%, together with conversion data for the 0.084-Mev gamma ray, showing that 3% remains unconverted for each total disintegration while 5% give *K* X-rays of 0.053 Mev, and 16% *L* and *M* X-rays which will be of 0.008 and 0.002 Mev. See Fig. 5. Measurements at Harwell, using proportional counter techniques, gave a close agreement for the relative emission and energy values of the main gamma and *K* X-radiation (*9*).

A millicurie calibration of Tm^{170} was made by coincidence counting methods using this decay scheme. The result, combined with *k*-factor measurements of the gamma and *K*-radiations made with various air ionization chambers, gave a value of approximately 45 mr/hr/mc at 1 cm.

To prepare compact sources of high density from the thulium oxide powder, metallurgical methods were adopted. By compression at about 10 tons to the square inch in carefully lubricated steel dies, a variety of small cylinders and disks was formed. Sintering was normally carried out in air using a platinum furnace, and a specific gravity between 7 and 8 was readily obtained in times ranging from 1 to 15 hours at a temperature of 1,550° C. Higher values could be achieved above this, but at about 1,750° C fusion with the alumina support was found to take place. Sources contract a little during sintering, and the final products are hard and durable.

FIG. 4. Am^{241} radiograph of a femur

The characteristic radiations of Tm^{170} are modified to some extent by the thickness and size of the solid source from which they are emitted. The two weak *L* and *M* conversion X-rays may be discounted because they will probably not emerge from a source or its enclosure, but the main gamma and X-radiation will be attenuated differentially in the source according to its thickness. The beta particles, which can be filtered when necessary, will give rise within a source to some bremsstrahlung of about 0.25 Mev, the amount of which will depend on size and shape of the source. This is illustrated by the absorption curves in Fig. 6, where it can be seen that with a thick source these secondary radiations

become significant as the softer components are filtered.

Tm^{170} for radiography. Tm^{170} is suitable for the nondestructive inspection of light alloys and other materials within the approximate density/thickness range of 1 to 10 gm/cm². By comparison with classical X-ray inspection techniques, the use of this material requires long exposure times with the source strengths that we can achieve at present in the available nuclear reactors. However, radioisotopes offer a new approach to inspection methods by virtue of minute source size, extreme portability, independence from electrical or other equipment, and very low cost. As the plate voltage can be altered on an X-ray machine, the isotope may be said to be less flexible and more restricted in range, but machine-made X-rays of a continuous spectrum may, in certain uses, be of less advantage than an isotope having one or more adjacent single-line spectra.

A typical set of exposure density curves for Tm^{170} is presented in Fig. 7. These were prepared from exposures with aluminum step blocks, at a range of 18 inches with Ilford Industrial B film. In this work, lead intensifying screens were used, a front screen thickness of 0.0015 inch, and a back screen of 0.005 inch being most efficient. The radiation energy of Tm^{170} is near the *K* absorption edge for gold, but the increased production of electrons with a gold screen is not sufficient to give a noticeably improved intensity.

Figures 1, 2, and 3, which are radiographs made with a Tm^{170} source, illustrate the usefulness of this isotope for examination of articles of different materials and thicknesses.

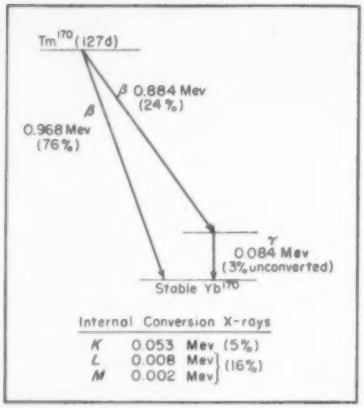

FIG. 5. Decay scheme for Tm^{170}

For the preliminary production at Harwell of Tm^{170} sources for radiography, a cylindrical size of 2 mm × 2 mm was chosen as a compromise between efficient activation, high radiation output, economy of material, and focal size considerations. Sources of about 300 mc each will be available. For safety and ease of handling, they are enclosed in standard capsules as illustrated on the left of Fig. 8.

Tm^{170} for thickness measurement. To measure the thickness of materials, Tm^{170} can be used in the same way as beta sources are used in existing types of thickness gages, provided that the detector is suitably sensitive to the soft gamma and X-radiation.

The useful range and order of sensitivity obtainable for this work is indicated by the attenuation curves shown in Fig. 6. They represent data for partly collimated beams from which beta particles were filtered by ¼-inch-thick Perspex. The detector was a Geiger-Müller tube with counting-rate meter, and the results were confirmed with an ionization chamber. With a scintillation counter, the attenuation curve is not as steep because the bremsstrahlung is counted more efficiently than the weak radiations.

Without filtration of the beta particles from a source, a steeper beginning to an attenuation curve may be obtained, but the particles may generate further bremsstrahlung if they fall on an absorber of high atomic number.

As a suitable shape for production (thickness-gaging) purposes, disks of 4 mm diameter × 0.4 mm thick are chosen. Sources of about 350 mc will be available. They are enclosed in aluminum capsules illustrated on the right in Fig. 8. The design of capsule allows the emergent radiation from the two opposite faces to be the same, allowing use in systems employing two detectors, the one with a reference standard absorber, and the other with the unknown or variable.

Americium

Americium-241 appears from preliminary experiments to have useful properties as a source of soft radiations. All the known isotopes of this element are radioactive and are formed from other transuranic elements. Am^{241}, with a half-life of 470 years, is formed by the neutron irradiation of plutonium, preferably for a significant proportion of the 10-year half-life of

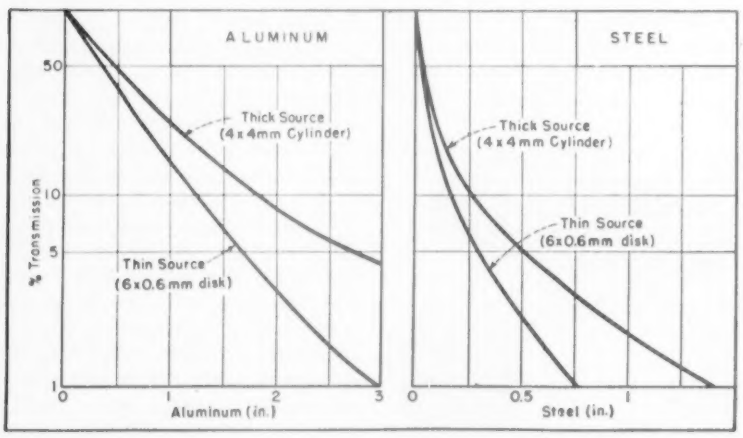

FIG. 6. Attenuation curves for Tm^{170} in aluminum (chart at the left) and in steel (chart at the right)

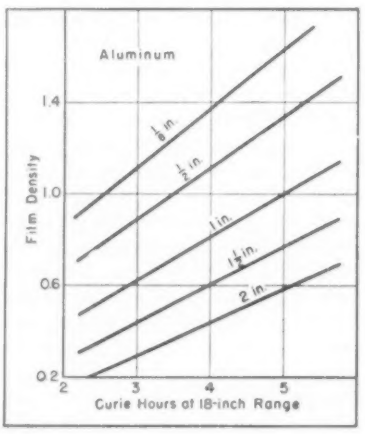

FIG. 7. Typical exposure density curves for Tm^{170} with aluminum

Pu^{241}. During and after irradiation of Pu^{240}, the Pu^{241} beta decays to, or "breeds" Am^{241} with the decay half-life of 10 years. The americium may be chemically extracted from the parent plutonium and will be carrier free. The specific activity which it must possess may be calculated as 3.2 c/gm.

The yield of this isotope is good, and already experimental quantities have been prepared. It is reasonable to assume that, with the use of plutonium-enriched reactors, Am^{241} may become available as a by-product.

A complete decay scheme for Am^{241} is not yet proposed, but it is clear from the work of Brown and Perlman (*10*), Prohaska (*11*), and others that the decay by 5-Mev alpha emission is followed by a 59-kev gamma-ray with some internal conversion X-rays of energies down to 14 kev. With a scintillation detector, attenuation measurements with a partly collimated beam of radiation gave a linear absorption characteristic of $\mu = 24.8$ in.$^{-1}$ for steel up to 0.15 inch in thickness and $\mu = 1.92$ in.$^{-1}$ for aluminum up to 1.6 inches in thickness.

As the radiations lie in the X-ray diagnostic range for the human body, the isotope is suitable as a medical radiography source. Figure 4 shows a femur radiographed using Am^{241}. Exposure was for 60 hours at a range of 6 inches on Ilford Industrial C film with a 6-mc source.

Europium and Xenon

Two other isotopes for use within the low-energy field have been suggested: Xenon-133 [Mayneord (*2*)] and europium-155 [Eastwood (*12*)]. Neither has so far been produced at Harwell in experimental quantities, but a consideration of the characteristics indicate their potentialities for wider employment, and data on them are given here to complete, so far as is known, the present survey of useful or potentially useful low-energy gamma-ray sources.

Europium-155 (1.7 years) is believed to decay by beta-particle emission of two groups, 0.25 and 0.15 Mev, followed by 0.1 and 0.085-Mev gamma rays of gadolinium-155 in the excited state (*13–17*). Rutledge, Cork, and Burson (*16*) also give evidence of two other gamma rays of a weak intensity, with energies of 0.13 and 0.06 Mev, and Wilson and Lewis (*17*) propose one other gamma emission of 0.015 Mev, together with Gd K and L X-rays of 0.040 and 0.005 Mev.

Eu^{155} can be obtained from the 25-min beta decay of samarium-155 produced from slow neutron capture (n,γ) by Sm^{154}. However, in Sm of natural isotopic content, the neutron capture cross section for this reaction ($\sim$1 barn) is in competition with that of Sm^{149} ($\sim 5 \times 10^4$ barns), and the yield is small.

Fission-product Eu^{155} has a yield of about 0.03% and, when extracted chemically, will be diluted with stable Eu^{151} and Eu^{153}, which are end products of samarium decay chains. A realistic value for the specific activity that should be obtainable is given as approximately 100 curies per gm (*12*).

Xenon-133 (5.3 days) is reported to decay by beta emission of 0.34 Mev, followed by a gamma ray of 0.081 Mev, which is largely converted internally. There is also evidence for an isomeric transition in Xe^{133} (2.3 days) giving a weak ($\sim$4%) gamma ray of 0.23 Mev, some of which is internally converted (*18–20*).

Xe^{133} may be prepared by the (n,γ) reaction from stable Xe^{132}, but the yield is low because of the low neutron capture cross section of 0.2 barns. Fission-product material offers the most useful yield, and a consideration of extraction methods (*21*) suggests that a concentration of the order of magnitude of 1 curie per 5 standard microliters would be obtainable, and that the short half-life may be offset by good availability from a batch extraction process.

The author wishes to acknowledge the co-operation of J. E. Evans in the measurement work with counters and ion chambers, and D. West and W. S. Eastwood in connection with proportional counter investigations of Tm^{170}. The help of A. E. Williams with sintering techniques is also gratefully acknowledged. Thanks are due to Dr. A. A. Moss of the British Museum Laboratories for permission to show his radiograph, and to Dr. R. L. Graham and his colleagues at Chalk River, Canada, for allowing the use of their results on Tm^{170} disintegration (see ref. 8). For permission to publish this article, acknowledgment is due the Director of the Atomic Energy Research Establishment, Harwell. (Crown Copyright is reserved by AERE, Harwell.)

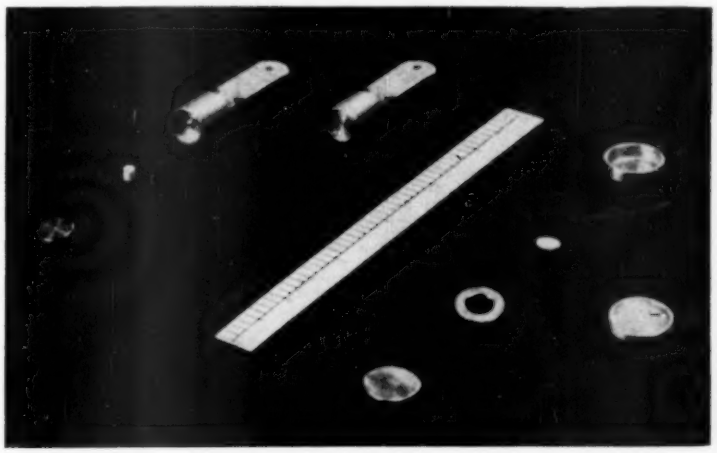

FIG. 8. Capsules and Tm^{170} sources for radiography are shown at left of inch ruler; those for thickness-gaging are at right

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Applications of Kicksorters

One of the best ways of measuring particle energies is with pulse-height analyzers. This article discusses the pros and cons of different types of analyzers, and the application of pulse-height analysis to coincidence counting

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PULSE-HEIGHT ANALYZERS, or kicksorters, provide a straightforward means for measuring particle energies. For such measurement, the kicksorter must be used in conjunction with a detector.

Energy Resolution

The over-all energy resolution of the experiment cannot be greater than that of the detector. The resolution obtained depends on the type of particle, its energy, and the detector used.

The resolution is usually limited in an ionization chamber by the Johnson, and other, noise associated with the amplifier. It is limited in a proportional counter by the stability of the voltage supply and the statistical scatter in the number of ions produced. And it is limited in a scintillation counter by the uniformity of light collection, uniformity of photocathode, and statistical fluctuation of the number of electrons from the photocathode.

The resolution of any method is reduced if the density of ionization along the track of the particle is great enough for recombination to be serious, or, in the case of a proportional counter, for the electrostatic field to be seriously disturbed; but the density must not be so low that the apparatus becomes too large. These criteria, together with conversion efficiency for γ-rays and neutrons, suggest the use of proportional counters for heavy particles with energies below a few Mev, and for quanta and electrons below about 30 kev. Ionization chambers should be used for heavy particles above a few Mev, and scintillation counters in all other cases.

Figure 1 shows some experimental resolution values. The quantity δE is the total width (expressed as an energy) of the peaks obtained on kicksorter diagrams, at the level of half their maximum height. For ionization chambers, δE should be nearly independent of E. In all other cases it should be proportional to $\sqrt{E}$, and this is seen to be roughly true.

Thus there are likely to be very few cases in which the resolution can be better than 1%, and there is little point in trying to make kicksorters whose stability of scale zero or constant of proportionality for translating channel number into pulse size is very much better than this. The linearity of the scale and the stability of the channel widths relative to each other are quite a different matter because errors in these can change the shape of the spectrum as distinct from its scale; these errors should be as small as possible.

Types of Kicksorters

In spite of the relatively low resolution as compared with magnetic deflec-

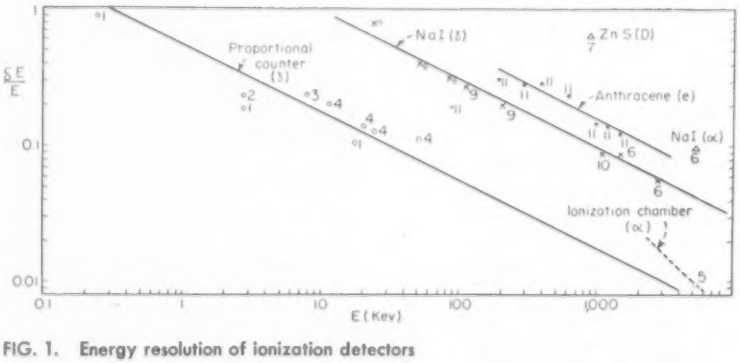

FIG. 1. Energy resolution of ionization detectors

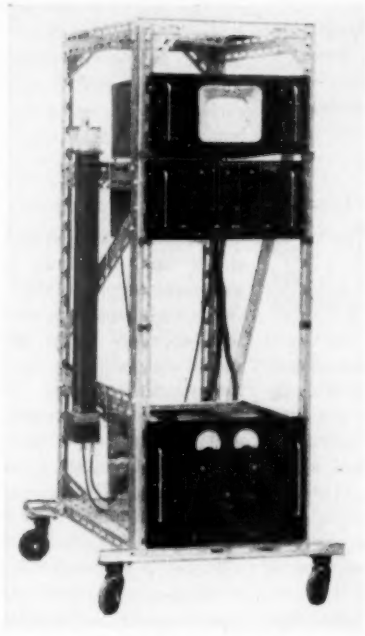

FIG. 2. Analyzer that converts voltage measurement into time measurement

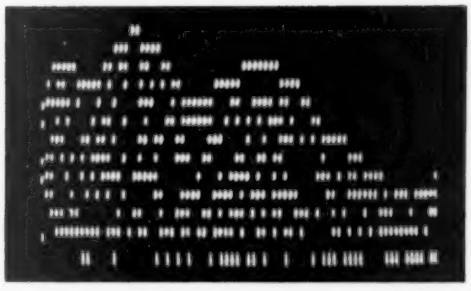

FIG. 3. Display of pulse spectrum on cathode-ray tube.

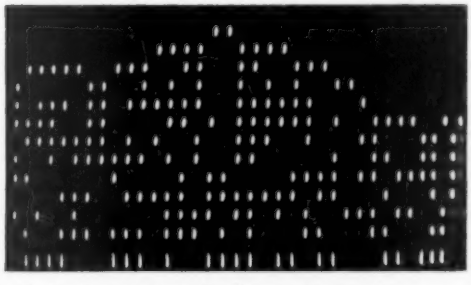

FIG. 4. Expanded display for reading results

tion methods, kicksorting is often so very much faster and more convenient that very many experiments can be done most readily in this way. There seems to be a case for three types of analyzers:

1. Single-channel kicksorters of high speed.

2. Multichannel kicksorters of moderate speed.

3. Multichannel kicksorters of low speed.

The speed of an analyzer refers to the maximum rate at which it can record pulses.

All analyzers are usually preceded by a biasing device to reject pulses less than a certain size. For a single-channel analyzer, the channel boundaries can be well spaced in voltage by means of a suitable amplifier after the bias, and so the use of different tubes to decide whether a pulse has gone over the lower and upper boundaries of the channel does not limit the accuracy of channel width seriously. Also, the information is stored as a single number, so it can be recorded in a conventional scaler or rate meter without too much complexity.

There is no reason why the operation time of such an analyzer should be more than a few microseconds—or even less than 1 μsec if necessary; and since it may sometimes have to precede the coincidence unit in a coincidence experiment, there is good reason to exploit its natural speed.

Single-channel analyzers have also been described in which pulses are selected from the screen of a cathode-ray tube by a photomultiplier (*12*), and these may prove even faster than those using two discriminators.

In multichannel kicksorters, the two difficulties are in defining the channel widths accurately enough, and in remembering and displaying the large number of separate data of a spectrum. The display is very important, for most of the spectra taken on an analyzer are only used as guides in adjusting experimental conditions, and are never taken down in permanent form. It is a great convenience to see the shape of the spectrum at a glance, and to reset to zero at will, both while setting up an experiment and while watching during a run.

At Cambridge, one solution to this problem is the analyzer (*13*) shown in Fig. 2. It uses, as its memory, the type of sonic delay line which has been developed for electronic computers. The stored information is circulated as a succession of impulses in this line and can be injected and changed by fairly simple circuits so as to represent a series of separate numbers, each written in a binary scale.

Pulse sizes are sorted by comparing the peak amplitude of a pulse with the continuously changing voltage of a linear saw-tooth waveform generated in the analyzer; this converts voltage to time measurement.

The channel boundaries are all determined by signals from an oscillator, and thus by the same set of components. The accuracy of the relative widths of the channels depends on the linearity of the comparison waveform and the oscillator frequency.

The spectrum is displayed at all times on a cathode-ray tube as shown in Fig. 3. Each vertical line of dots represents the number of pulses in one channel on a binary scale (2° at the bottom); the x-coordinate of any line is a linear function of the corresponding pulse size. The outline of bright dots thus gives a logarithmic spectrum. When reading off the numbers, the spectrum can be expanded (Fig. 4).

How many channels should a kicksorter have? Certainly not so many that the zero error of the analyzer is comparable with channel width; but we are not often near this limit. It is best to use the smallest number of channels which will define the spectrum with sufficient accuracy; more

channels only pile up irrelevant data. In this respect, this type of analyzer is very flexible. At a given speed of operation, the storage capacity per channel (number of binary digits) and the number of channels are interchangeable. For a given capacity per channel, the number of channels is roughly proportional to the length of the delay line, and thus inversely proportional to the maximum counting rate. The choice can be made in both cases by a single switch.

The table shows the number of channels possible, at different values of speed and storage capacity, in kicksorters that use a dynamic memory and a comparison-waveform sorting mechanism, when the interval between digits in the memory is 1 μsec.

Possible Numbers of Channels for Various Maximum Counting Rates

Capacity per channel (counts)	*Number of channels at:*		
	5,000 cps	*1,600 cps*	*500 cps*
$2^{10} \approx 1{,}000$	35	106	400
$2^{14} \approx 16{,}400$	25	78	280
$2^{20} \approx 10^6$	17	53	200

Although the maximum counting rate is limited by the delay-line length, pulses can be fed into the kicksorter at a much higher rate without distorting the spectrum. This is because the gate before the sorting circuits is closed while the analyzer is digesting a pulse and reopened only when it is ready to receive another pulse. In this way the kicksorter takes a random pulse sample, independent of pulse size.

Spectra will be distorted either if pulses follow each other so closely that they sometimes fall on top of one another (when they will appear too large), or if they arrive when the gate is half open (in which case they will appear too small). The pulse rate at which these two errors become serious should be about the same. The reasons are as follows.

The type of gate usually employed for pulses in the time range from fractions of a microsecond upwards is shown in Fig. 5. This gate is clearly symmetrical in its operating-current requirements between "signal" and "gate" terminals, and can therefore be operated as fast as pulses can be amplified in conventional feedback amplifiers. The total fraction of each second during which the gate is in process of opening or closing need not, therefore, be greater than the total time occupied by pulses, even if the gate is operated after every pulse.

In the rare cases when these errors are serious, they can both be eliminated completely by using an inspection circuit such as has been described by Kelley (*14*). This circuit rejects any two pulses falling too close together in time, and this can be applied as well to the overlap of the gating signal with a pulse as to the overlap of two incoming pulses. Thus the use of a gate need never lead to spectrum distortion. Most multichannel kicksorters can deal with very much higher pulse rates if they have a gate.

Some experiments can use a much slower kicksorter, and in these cases a mechanical one is simpler and cheaper. Such a type has been described by Frisch, Scarrott and Frank (*15*).

There does not seem to be any good case for very high speed multichannel kicksorters, simply because it is useless to accumulate data at a rate very much greater than that at which it can be assimilated, or to do experiments in a much shorter time than they can be set up.

Suppose we have a 60-channel kicksorter with a maximum rate of 1,000 cps, and suppose half the channels are counting appreciable numbers of pulses. If numbers in these channels are to be determined to 1% (which is only occasionally justified), we must count 30×10^4 pulses; this can be done in 5 min. Even if the machine prints the 60 numbers, the information would be far more than the experimenter can assimilate in 5 min. If only a small part of the information is required—say the height of one peak—this often means that the analyzer is not being used to the best advantage. The unwanted information can usually be excluded by adjusting the amplifier and bias settings and using a kicksorter of fewer channels.

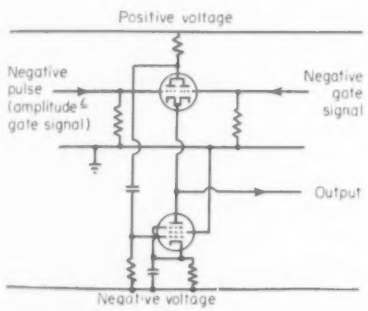

FIG. 5. Gate for pulses shorter than a microsecond

Coincidence Experiments

The half-life of short-lived nuclear states can sometimes be found by measuring the coincidence rate between two detectors as a function of the (variable) delay introduced into the circuit between one detector and the coincidence unit. This is preferable to use of a coincidence circuit without delay, and with variable resolving time, for the same reason that a single-channel kicksorter is preferred to a discriminator—because it gives information of greater statistical significance in a given time.

Delayed coincidence counting is most useful up to times of the order of milliseconds; for longer times, the permissible counting rate becomes inconveniently low. However, there must be only a small probability that another nucleus in the sample will radiate during a time comparable with the characteristic interval between emission of the particles whose delayed coincidence is being measured.

All measurements of this kind, and also all measurements of slow-neutron cross sections by time-of-flight methods, can very easily be translated into experiments in pulse-size analysis by the type of circuit shown in Fig. 6 (*16*). In this way, multichannel kicksorting techniques can be used with great advantage, because a range of time intervals can be investigated at once instead of one after another.

The shortest time that can be measured depends on the rise times and random delays of the pulses from the detectors. The limit to the precision in time with which a pulse can be recorded by this method has been given (*17*) as about 3×10^{-10} sec, and it appears that this limit has nearly been reached.

Very many interesting nuclear states have half-lives much shorter than we can so far measure. We can, however, get information about them by doing coincidence experiments on particles which are emitted in the formation of the state and on its breakup. All angular-correlation experiments are in this class, and since these form a large

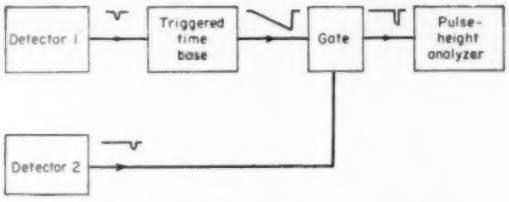

FIG. 6. Use of a kicksorter in coincidence experiments

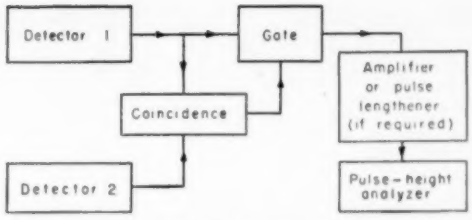

FIG. 7. Reduction of ratio of random to real coincidences

part of current nuclear work, the technique of coincidence counting is very important. The chief requirements are fast detectors and coincidence circuits to increase the counting rate at which the number of random coincidences approaches the true coincidence rate.

The random coincidence rate is $N_1N_2(T_1 + T_2 - 2T_0)$, where N_1 and N_2 are the total numbers of counts per second in the two detectors, T_1 and T_2 are the lengths of the pulses (idealized as square) which they transmit to the coincidence gate, and T_0 is the minimum pulse-overlap time needed to produce an output pulse.

The real coincidence rate is $kn^*\epsilon_1\epsilon_2$ where n^* is the rate at which the source emits either of the two types of particle whose coincidences are being measured, and ϵ_1 and ϵ_2 are the over-all efficiencies of the two detectors. The factor k (≤ 1) is determined by the ratio of $(T_1 + T_2 - 2T_0)$ to the uncertainty of the relative time of emission of the particles, and of the delays in the detectors and circuits; k tends to unity when this ratio is large. Thus the ratio of random to real counts is

$$\frac{N_1N_2(T_1 + T_2 - 2T_0)}{kn^*\epsilon_1\epsilon_2}$$

If we consider the factors of this expression in turn, and assume that conditions have been chosen so that $k = 1$, we can see that for a constant, real counting rate, the real-to-random ratio can be improved by making N_1 and N_2 as small as possible, and by making $2T_0$ nearly equal to $T_1 + T_2$. Most effort is usually put into the latter factor, using delay-line pulse shapers and crystal coincidence circuits to make T_1, T_2, and T_0 all small. This is, of course, better, from the point of view of stability, than trying to make $2T_0 = T_1 + T_2$ while all are large. But having made T_1 and T_2 as small as possible, the shortest resolving times can then be obtained by selecting T_0. This is effectively what is done in a circuit described by Bay, Meijer, and Papp (*18*), in which a normal coincidence circuit is vetoed if a pulse is produced from a circuit measuring the presence of a signal from either detector in the absence of a signal from the other.

The reduction of N_1 and N_2 may be just as important as the reduction of T in improving the real-to-random ratio. If the detectors give negligible background counts in the absence of the source, then $N_1 = n_1\epsilon_1$ and $N_2 = n_2\epsilon_2$, where n_1 and n_2 are the rates of emission, by the source, of particles to which the two detectors are sensitive. In this case

$$N_1N_2/n^*\epsilon_1\epsilon_2 = n_1n_2/n^* = \alpha_1\alpha_2n^*$$

where $\alpha_1 = n_1/n^*$ and $\alpha_2 = n_2/n^*$. Since n^* is fixed for a given real counting rate, the only factors we can hope to reduce are α_1 and α_2.

The first way to do this is to purify the source as much as possible, and to make each detector sensitive to only one type of particle by a suitable choice of detector and screening. But there are still often several different energies of, say, γ-quanta emitted by the source, only one group of which will be in real coincidence with the particles firing the other detector. Under these circumstances, the use of single-channel kicksorters in one or both arms of the coincidence circuit may often be worth while (*19*), even at some loss of resolving time, since this is effectively a way of reducing α.

A still better solution would sometimes be to use a multichannel kicksorter in the way shown in Fig. 7. True coincidences are then recorded in one or more distinct peaks of the pulse spectrum, while the rest of the channels give a continuous check of the random rate. In this case, as we have seen, the resolving time is limited by the gate circuit, and not by the pulse-height analyzer, which can often be quite slow.

The other consideration in reducing the random-to-real ratio is the detector background. This increases N_1N_2 independently of real counting rate.

The random delays in scintillation counting are smallest when the coincidence circuit works at a level corresponding to the emission of very few electrons from the photocathode—in the limit, to the emission of the first electron of a pulse (*20*). Thus in fast coincidence work, there is a tendency to increase the gain of the multipliers or decrease the bias level of the coincidence circuit; but as the "single-electron limit" is approached, the background count increases very sharply, and the increase in N_1N_2 may very quickly offset the decrease in T. This is a point which must always be considered very carefully when trying to improve the counting rate in a coincidence experiment. It may even pay well sometimes to use a slower phosphor if it will produce larger pulses which can be separated more easily from the background, or a better resolution of particle energies.

* * *

This article is based on a paper presented at the Third Instruments and Measurements Conference, Stockholm, Sweden, Sept. 22, 1952.

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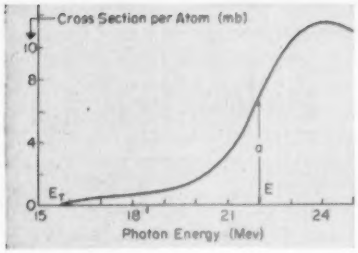

FIG. 1. Cross section for reaction $O^{16}(\gamma,n)O^{15}$ as function of energy of incident photon

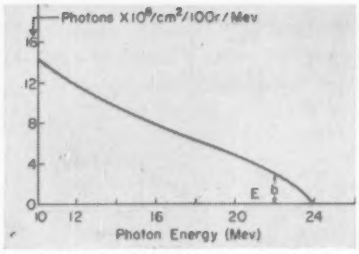

FIG. 2. Modified bremsstrahlung spectrum at peak energy of 24 Mev (from reference 4)

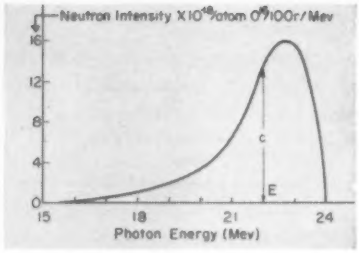

FIG. 3. Neutron intensity from O^{16} with betatron operating at maximum energy of 24 Mev

Energy Absorption in Human Tissue by Nuclear Processes with High-Energy X-Rays

Cancer patients undergoing treatment with a 24-Mev betatron have been studied to determine the biological effect of the additional ionization resulting from photonuclear processes produced by the high-energy X-rays. Total absorption is not appreciably increased

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SINCE 1949 the 24-Mev betatron at the University of Saskatchewan has been used to treat certain advanced types of cancer. The main biological effect is attributed to energy absorption in the conventional manner, that is, by the Compton effect and pair production, which results in the production of high-speed positrons and electrons. These high-speed electrons and positrons lose energy by causing ionization in the tissue. With high-energy X-rays, other processes, involving nuclear absorption of the photons, and emission of energetic neutrons, protons, and alpha particles are possible. These energetic particles can cause dense ionization along their paths and could conceivably add to the biological effect.

In 1949, Mayneord, Martin, and Layne (*1*) considered the effect of the energy absorbed due to the induced radioactivity. Since that time photonuclear cross sections have been measured in this laboratory and elsewhere for many of the low-atomic-number elements, and we are now in a position to examine this problem in greater detail. It is the purpose of this paper to estimate the total energy absorbed in tissue due to nuclear effects with high-energy X-rays, and indicate its importance in relation to the energy absorbed in the conventional manner.

Composition of Tissue

A percentage composition by weight of wet tissue shows that hydrogen, carbon, nitrogen, and oxygen make up 99% of the tissue (*2*). In the calculations that follow, only carbon (12%), nitrogen (4%), and oxygen (73%) are considered because there is no nuclear absorption in hydrogen. The nuclear processes in the less abundant elements of tissue will be neglected since their contribution must be small in comparison to that of carbon, nitrogen, and

TABLE 1—Energy Absorbed in Tissue with 24-Mev Bremsstrahlung

Element	Ergs per gram per 100 r			
	(γ,n)	(γ,p)	(γ,α)	Total
C^{12}	2.0	10.0	0.8	12.8
N^{14}	3.4	29.2	...	32.6
O^{16}	2.8	25.3	4.3	32.4

TABLE 2—Energy Absorbed from Activity Induced in One Gram of Isotope, with 24-Mev Bremsstrahlung

Isotope	Neutron yield per 100 r per gm of isotope at 24 Mev	Maximum positron energy (Mev)	Mean energy (Mev)	Energy absorbed (ergs/gm)	Energy absorbed due to annihilation radiation (ergs/gm)	Total energy absorbed due to induced activity per 100 r (ergs/gm)
C^{12}	36.2×10^4	0.99	0.33	0.19	0.58	0.58
N^{14}	25.6×10^4	1.24	0.41	0.17	0.41	0.44
O^{16}	28.3×10^4	1.68	0.56	0.25	0.45	0.55

oxygen. Only nuclear processes connected with the C^{12}, N^{14} and O^{16} isotopes need be considered.

24-Mev Bremsstrahlung

A nucleus, after capturing a high-energy photon, may emit a neutron, proton, or alpha particle, or combinations of these particles, providing the energy of the incident photon is greater than the threshold energy for the emission of the particle, or particles. With 24-Mev radiation, mainly single-particle emission need be considered for C^{12}, N^{14} and O^{16}, since the cross section for two-particle emission is very small, or the reaction has too high a threshold.

These ejected particles may have large kinetic energies. For example, when an O^{16} nucleus captures a 24-Mev photon and emits a proton, the difference in energy between 24 Mev and 12.2 Mev, the threshold energy for emitting a photon, must be shared by the recoiling nucleus and the emitted proton. The kinetic energy of the proton in this case would be $^{15}/_{16} \times$ 11.8 Mev, or 11.07 Mev. The kinetic energy of the recoiling nucleus would be 0.73 Mev. On the other hand, if an alpha particle or neutron were emitted, energies of 16.6 and 8.4 Mev would be shared between the recoiling nucleus and the emitted alpha particle or neutron, respectively.

In some cases, however, it might be that the energy to be shared is only part of the difference in energy between the incident photon energy and the threshold value. The remainder of it would appear in the form of several low-energy de-excitation photons as the excited nucleus settles down into its ground state. Most of the latter energy would be absorbed by the tissue in the conventional manner.

In the case of neutron emission from the nuclei, the ionization in the tissue will not be caused by the neutrons themselves. The neutrons will be slowed down mainly by collisions with hydrogen nuclei, which then cause ionization in the tissue.

In the calculations that follow, it is assumed that all the difference in energy between the incident photon and the threshold energy is absorbed by the surrounding tissue. Then the value obtained for the energy absorption will be an upper limit.

Calculations

Figure 1 shows the cross-section curve as a function of the incident photon energy for the reaction $O^{16}(\gamma,n)O^{15}$ as determined in this laboratory (*3*). The shape of the 24-Mev bremsstrahlung spectrum is based on a formula due to Schiff that gives the relative intensity in the forward direction as a function of the betatron energy. Johns *et al.* (*4*) have modified this spectrum to allow for absorption in the betatron donut, a monitor ionization chamber, and 4 cm of Lucite. The results were then multiplied by the response curve of the Victoreen r-meter and normalized to make the total dose 100 r. The normalized bremsstrahlung spectrum obtained in this way is shown in Fig. 2.

The amount of energy given to the tissue through the (γ,n) reaction in O^{16}, when tissue is irradiated with X-rays of peak energy 24 Mev, will be determined as an example. If one takes the product of the ordinate a of Fig. 1, and b of Fig. 2, one obtains the number of neutrons liberated per atom of O^{16} per 100 r per Mev interval at energy E. If we assume for the moment that the neutron receives all the available energy, then the energy given to the neutron is the difference between the threshold energy E_T and the energy of the interacting photon E. The product $ab(E - E_T)$ gives the ordinate c of Fig. 3, which is the neutron intensity per 100 r per atom of O^{16} per Mev interval.

The area under the curve of Fig. 3 gives the total energy imparted to neutrons. In actual fact, however, some of this energy reappears as recoil energy and perhaps also in the form of de-excitation photons, but the value of the area still represents the energy absorbed due to the (γ,n) process. The value of the area expressed in ergs per gram of O^{16} is shown in Table 1. Similar values for energies absorbed per gram of C^{12} and per gram of N^{14} due to the $C^{12}(\gamma,n)C^{11}$ and $N^{14}(\gamma,n)N^{13}$ reactions are also tabulated (*3*, *5*).

Similar calculations have also been made for (γ,p) reactions in carbon, nitrogen and oxygen. The cross section for $C^{12}(\gamma,p)B^{11}$ has been determined by Mann and Halpern (*6*). Cross-section curves for the $O^{16}(\gamma,p)N^{15}$ and $N^{14}(\gamma,p)C^{13}$ reactions are not available. However, the $O^{18}(\gamma,p)N^{17}$ cross-section curve (*7*, *8*) is known, and it is assumed that the shapes of the $O^{16}(\gamma,p)N^{15}$ and $N^{14}(\gamma,p)C^{13}$ cross-section curves are similar. Curves for the latter two reactions have been plotted and made identical in shape to the $O^{18}(\gamma,p)N^{17}$ curve but starting at the appropriate calculated threshold energies for the two (γ,p) reactions. The absolute values for these curves were obtained from the work of Mann and Halpern (*9*) who measured the proton yield with 23.5-Mev bremsstrahlung. By interpolating between their values for carbon and magnesium, we have estimated the proton yield from nitrogen and oxygen. The absolute value of the assumed cross-section curve was determined by normalizing the calculated proton yield to the value obtained from Mann and Halpern's data. The energy absorbed due to the (γ,p) reac-

tions in N^{14} and O^{16} as determined from these calculated cross-section curves is shown in the third column of Table 1.

Energy absorbed in tissue due to the $C^{12}(\gamma,\alpha)Be^{8*}$ and $O^{16}(\gamma,\alpha)C^{12}$ reactions using cross-section curves obtained by other investigators (*10, 11*) is shown in column 4 of Table 1. Sufficient data are not available to determine the energy absorption due to the (γ,α) reaction in N^{14}. However, this is not a serious omission since only 4% by weight of tissue is nitrogen.

The sum of the energies absorbed is tabulated in column 5 of Table 1. The energy absorbed per gram of N^{14} or O^{16} is about 2.5 times as large as the energy absorbed per gram of C^{12}. This difference can be attributed mainly to energy absorbed in the (γ,p) processes. (See column 3). More energy is absorbed per gram of O^{16} and N^{14} than per gram of C^{12} because the threshold energies for the (γ,p) reactions in N^{14} and O^{16}, 7.5 and 12.2 Mev, respectively, are lower than the threshold energy 16.2 Mev for the (γ,p) reaction in C^{12}.

In the case of proton or alpha-particle emission from C^{12}, N^{14} or O^{16}, the product nucleus is stable except for Be^8, which disintegrates into two alpha particles. However, after ejecting a neutron, the product nucleus C^{11}, N^{13} or O^{15} is left in an unstable state and will emit a positron some time later. The positron will produce ionization in the tissue and lose its energy.

The neutron yields at 24 Mev (*3, 5*) per gram of isotope per 100 r are tabulated in Table 2. This gives the total number of positrons which will be absorbed by the tissue. The maximum energy of the positrons in each case is given but, since the positron may have any energy up to its maximum value, the mean energy of the positrons for these calculations is assumed to be equal to one third the maximum possible energy. The energy absorbed in tissue per gram of element is then the product of the yield times the mean energy of the positron. This value is given in column 5, Table 2.

In the case of positron emission, the beta particle at the end of its path will unite with a negative electron, and 1.02 Mev in the form of two annihilation quanta will be created. These eventually will be absorbed in the conventional manner. Therefore, for every β^+ particle emitted, 1.02 Mev of annihilation radiation will be created and also absorbed if the scattering medium is large enough. This energy absorption is given in column 6. Calculations show, however, that in the "average patient" about two thirds of this energy will be absorbed. Consequently, two thirds of the quantities shown in column 6 have been added to those of column 5 to yield the total energy absorbed, in the last column.

The energy liberated due to annihilation radiation is two to three times as large as that due to ionization by the positrons. Comparison of Tables 1 and 2 shows that the energy absorption due to the induced radioactivity is small compared to that liberated by the heavy particles set in motion.

IN CHECK for induced radioactivity, counter is taped over patient's right anterior chest, which is spot where X-rays entered body from betatron seen at right

The energy absorption per gram of isotope per 100 r with 24-Mev bremsstrahlung due to the emission of a proton, neutron, or alpha particle, Table 1, plus the energy absorbed in the tissue due to the induced radioactivity, Table 2, is shown in the first three values in column 2, Table 3.

Energy Comparison

The energy absorbed directly from the X-ray beam per gram of tissue per 100 r is 9,300 ergs. The energy absorbed in tissue due to nuclear effects (27.0 ergs) amounts to about 0.3% of this value. Hence, on the basis of energy absorption, it is unlikely that the biological effect of 24-Mev X-ray radiation will be influenced by nuclear processes. However, it should be remembered that the density of ionization for alpha particles, protons, and recoiling nuclei is many times larger than that produced by electrons.

One of the factors which is known to influence the biological effect produced by an ionizing radiation is the density of ions produced. Therefore, it probably is not enough to compare the energy absorbed by the different methods without considering the density of the ion tracks. This would be a formidable if not impossible task, considering the various types of particles involved.

Perhaps it would be sufficient to multiply the energy absorbed in tissue due to nuclear processes by some factor which would help to compensate for the difference in ion densities. However, it is very difficult to determine this factor. One method of estimating its value is as follows. Most of the energy loss in tissue due to nuclear reactions is caused by protons, alpha particles, and recoiling nuclei. The density of ionization produced by protons is less than that produced by alpha particles. On the other hand, the density of ionization produced by recoiling nuclei is greater.

As a rough estimate, the biological effects produced by all the nuclear events may be, on the average, comparable to the biological effects produced by alpha particles. If we assume that alpha-particle radiation is ten times as effective as X- or gamma radiation in producing a biological effect, up to 3% of the biological action produced by 24-Mev bremsstrahlung radiation can be attributed to nuclear events. It is unlikely that the effect could be any larger than this and hence would be very difficult to detect.

Chemical Changes

It is conceivable that some biological effect might result from chemical changes due to nuclear transformations. For instance, C^{12} after capturing a photon may emit a neutron and so change to C^{11}. This in turn decays by positron emission to B^{11}, which is stable. In one gram of tissue, there occur about 10^6 nuclear changes per 100 r of 24-Mev X-ray radiation. For an average total dose of about 7,000 r, there will be about 10^8 nuclear changes per gram of tissue. Since there are about 10^{22} atoms in one gram of tissue, this represents a small percentage change, but perhaps could be enough to have a small biological effect.

Higher X-Ray Energies

The absorption of energy in tissue due to nuclear processes at X-ray energies higher than 24 Mev is more difficult to estimate since many reactions involving the emission of more

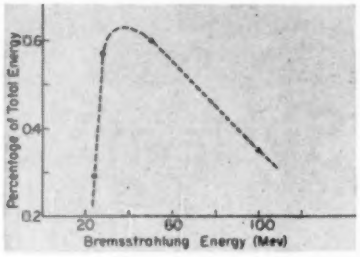

FIG. 4. Percentage of total energy absorption in tissue due to nuclear processes

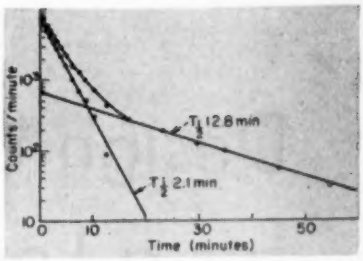

FIG 5. Decay curve of induced radioactivity in patient receiving 408 r at 24 Mev

than one particle are energetically possible. Very little is known about the magnitude of these reactions.

Recent work (*12*) done in this laboratory on the photonuclear reactions in fluorine indicate that the $(\gamma,2n)$ integrated cross section is about one eighth the (γ,n) integrated cross section. From this we assume that the cross section of carbon, nitrogen, and oxygen for emission of two or more particles is at least an order of magnitude less than the cross section for single particle emission. In addition, experimental work done by Perlman and Friedlander (*13*) and Holtzman and Sugarman (*14*) indicate that the yields of nuclear reactions at 50 Mev in carbon and oxygen, which involve the emission of more than one particle, are about one fiftieth or less the yields of reactions in which single particles are emitted. Therefore, the error in our calculations is small if we neglect the contributions from reactions involving the emission of two or more particles.

On this basis, the energy absorption in tissue due to nuclear reactions has been calculated at 28, 50, and 100-Mev bremsstrahlung energies and the values obtained are also shown in Table 3. The details of the calculations are the same as for 24-Mev bremsstrahlung except that the modified Schiff spectra for 28, 50, and 100 Mev are used.

The percentage of the total energy absorbed in tissue which is attributed to nuclear reactions is plotted in Fig. 4 as a function of the peak X-ray energy. It is seen that the maximum effect, amounting to about 0.6%, occurs in the energy region from 30 to 50 Mev. If we increase this value arbitrarily by a factor of 10, as before, to account for the difference in ion densities, about 6% of the biological effect may be attributed to nuclear reactions in the 30- to 50-Mev energy region. At energies above and below this region the effect becomes smaller. At any energy up to 100 Mev, however, the energy absorbed in tissue due to nuclear effects is relatively small.

Clinical Observations

Since 1949, about 125 patients with various advanced types of cancer have been treated with the 24-Mev betatron at the University of Saskatchewan (*15*), by Dr. T. A. Watson, Director of Cancer Services. No special biological effects were noticed which could be attributed to nuclear processes occurring in the patients. This is in agreement with our calculations.

The induced radioactivity in one of these patients was measured as follows. A Geiger counter was fastened securely to the right anterior chest of a male patient directly over the position where the X-ray beam had entered his body. See the photograph at the left. The patient had just received a dose of 408 r at 24 Mev. The activity was followed for one hour and the resulting decay curve is shown in Fig. 5. An analysis of this decay curve gives a 2.1-min half-life, which is attributed to the 2-min O^{15} positron activity, and a 13.5-min activity. The latter activity could be attributed to a combination of the 10-min N^{13} activity and the 20.6-min C^{11} activity.

TABLE 3—Total Energy Absorbed in Tissue from Reactions Produced by Bremsstrahlung of Various Energies

Isotope	*Energy in ergs/gm of isotope per 100 r*	*Percentage composition by weight in tissue*		*Energy in ergs/gm of tissue per 100 r*
24 Mev				
C^{12}	13.4	12		1.6
N^{14}	33.0	4		1.3
O^{16}	33.0	73		24.1
			Total	27.0
28 Mev				
C^{12}	21.7	12		2.6
N^{14}	44.9	4		1.8
O^{16}	66.9	73		48.9
			Total	53.3
50 Mev				
C^{12}	21.3	12		2.5
N^{14}	39.6	4		1.6
O^{16}	71.0	73		51.9
			Total	56.0
100 Mev				
C^{12}	12.6	12		1.5
N^{14}	20.8	4		0.8
O^{16}	41.5	73		30.3
			Total	32.6

Conclusions

The energy absorption in tissue due to nuclear reactions amounts to at most 0.6% of the energy absorbed in the conventional manner. Most of this energy absorption results from the setting in motion of heavy particles such as protons, neutrons, alpha particles and nuclei. Even if we arbitrarily increase this value by a factor of 10 to allow for differences in ion density, it is unlikely that nuclear absorption is of any appreciable biological significance. The percentage change in chemical composition due to nuclear transformations is very minute, and unlikely to be of biological importance.

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Design of a Control System for a Low-Cost Research Reactor

The control system of the ORNL "swimming pool" reactor, basis for the design described in this article, has had two years of trouble-free operation. Most of the ionization chambers and other control instruments are commercially available

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SINCE A LOW-COST research reactor will be used principally as a neutron source (*1*), the control system should provide reproducible fluxes over a wide range of operating levels, as well as adequate protection of personnel against operational hazards. While the system described is basically that of the ORNL "swimming pool" reactor (*2*, *3*), this article is intended as a guide in solving problems encountered in designing such a system. The commercial instruments described were not designed specifically for the ORNL reactor. Proper redesign should produce savings in cost and space.

The reactor to be considered is a water-cooled and moderated thermal system using enriched uranium (>90% U^{235}) for fuel. Twelve to sixteen aluminum-uranium alloy fuel elements 3 in. square by 24 in. long, placed on end in an aluminum grid, form the active lattice. The active lattice is submerged in a pool of water. A depth of approximately 16½ ft of water above the top of the lattice provides protection from radiation for personnel at the operating power level of 100 kw.

Neutron Balance

Since the equations governing the kinetic behavior of a reactor have been treated in detail elsewhere (*4*, *5*, *6*), we will limit our discussion to a few necessary comments.

A convenient quantity often used in speaking of the control of a nuclear chain reaction is the reactivity, ρ

$$\rho \equiv \frac{k_{eff} - 1}{k_{eff}}$$

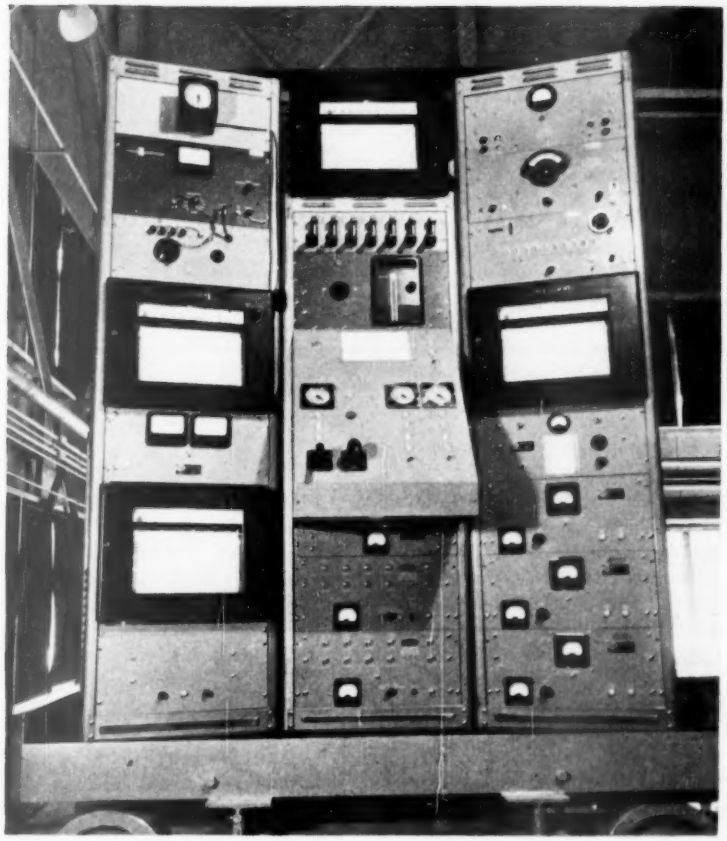
where k_{eff} = effective multiplication constant of the reactor.

For a given system, the period of rise or fall of reactor fission rate is related to ρ by the reactor kinetic equations. In these equations, the reactor is shown to be self-sustaining, in the steady state, by the establishment of a neutron balance. A fraction of the neutrons, β ($\approx 0.7\%$), does not appear immediately after fission but at a later time, of the order of seconds, as the delayed emitters decay and release neutrons which help maintain the reaction.

For ρ negative, the neutron flux will decrease in a period largely determined by the half-lives of the delayed emitters. For ρ positive, but small compared to β, the neutron flux will increase in a period largely determined by the half-lives of the delayed neutron emitters. As ρ approaches β, in sign

TABLE 1—Reactivity and Reactor Period

ρ	T (sec)
+0.001	60
+0.003	10
+0.007	0.2
+0.01	0.04



CONTROL PANEL and some operating instruments of the ORNL low-cost reactor

and magnitude, the period becomes shorter, and for ρ equal to β the chain reaction can be sustained without the contribution of the delayed emitters. This condition is termed "prompt" critical. For ρ greater than β, the period becomes even shorter.

Table 1 shows some approximate figures relating ρ to the reactor period, T. The reactor period is the time required for reactor flux level to change by a factor of e. From Table 1 it can be seen that an available ρ of about $+0.003$ is sufficient to permit the power level to be changed over wide ranges in reasonable lengths of time, with considerable leeway before reaching periods so short that extreme demands are put on the safety system.

Excess Reactivity Requirements

Several different effects contribute to the change in reactivity of a reactor while it is operating. Let us consider these one at a time and then estimate the total excess reactivity necessary for satisfactory operation of the reactor. A ρ of $+0.003$ will be taken as sufficient to permit the operator to change power levels.

Temperature changes. This reactor has an over-all temperature coefficient of reactivity of -7.5×10^{-5}/°F. In operation at 100 kw, with convection cooling, the temperature rise of the water passing through the reactor is about 20° F. This ΔT results in an increase in average temperature of the water in the core of 10° F. The large heat capacity of the water in the pool prevents rapid changes in the temperature of the inlet water; however, there are changes resulting from reactor operation, from seasonal temperature variations, and from changing the pool water for one reason or another.

If we assume the variation in pool temperature is no greater than 40° F, i. e., from the lowest temperature to the maximum temperature, we have a total change in average temperature of the water in the reactor core of 50° F from operation at very low power, with fresh, cold water in the pool, to operation at 100 kw with warm water. This temperature range corresponds to a change in reactivity of $\rho = -0.00375$.

Fuel burnout. It is desirable that fuel additions to compensate for depletion due to fuel burnout need not be made at intervals any shorter than 100 days. The loss due to burnout of fuel can be estimated from the fact that approximately 1.2 gm of U^{235} undergoing fission results in one megawatt day of energy. Operation at 100 kw will burn out 12 gm of fuel in 100 days, or approximately 0.4% of the fuel in a reactor containing 3 kg of U^{235}. The percentage change in reactivity is somewhat less than the percentage change in fuel concentration, about $\frac{1}{3}$ for this reactor; therefore $\rho = -0.0015$ due to fuel burnout.

Fission-product poisoning. In the fission process, the U^{235} is lost (burned out), and a variety of different elements result. For the most part, the contribution of these new elements may be neglected in estimating the decrease in k_{∞}; however, two products, Xe^{135} and Sm^{149}, are of some interest and should be considered due to their extremely large cross sections for absorption of neutrons (7). The thermal cross section of 9.2-hr Xe^{135} (3.5×10^6 barns) is several orders of magnitude greater than that of U^{235} (650 barns) or of boron (750 barns) which is used for control rods. Xenon-135 results from 5.9% of the fissions, either directly (0.3%) or through the decay of 6.7-hr I^{135} (5.6%) (8). Solution of the differential equations governing the buildup and decay of I^{135} and Xe^{135} yield the following steady-state solution for long-time operation of the reactor (4).

$$N = \frac{(y_1 + y_2)\Sigma_f \phi}{\lambda_2 + \sigma_2 \phi}$$

where N = the number of Xe^{135} atoms/cm³, y_1 = fraction of fissions leading to I^{135}, y_2 = fraction of fissions leading directly to Xe^{135}, Σ_f = macroscopic fission cross section, ϕ = neutron flux, λ_2 = decay constant for Xe^{135}, and σ_2 = Xe^{135} absorption cross section.

For this reactor, operating at 100 kw, $N \approx 1.4 \times 10^{14}$ atoms/cm³. Expressing this in terms of reactivity, we find $\rho = -0.0045$. A large fraction of this value is reached in a 24-hr period of operation. This poison decays, as governed by the half-lives of I^{135} and Xe^{135}, on shutdown of the reactor.

Samarium-149 has a thermal neutron absorption cross section of 5.0×10^4 barns. This stable isotope is formed

from the β^- decay of 47-hr Pm^{149} and does not decay after reactor shutdown. The equilibrium concentration is independent of the magnitude of the flux and approaches a value of $\rho = -0.012$ (*4*). The time to attain equilibrium is inversely proportional to the magnitude of the flux; in this reactor, operating at 100 kw, the time to approach equilibrium is roughly 4 yr, and therefore this poison can be neglected in this estimate.

Experiment allowance. Experiments placed next to the core will absorb neutrons which might otherwise be reflected back into the active lattice by the water. These losses are dependent on the type of experiment and therefore will be different for different setups. Experience indicates that $\rho = -0.02$ is not an unreasonable figure. The reactor loading can be changed at the time experiments are put in so that the normal excess reactivity is limited to the amount necessary to meet operational requirements.

Table 2 is a summary of the requirements for excess reactivity. From the information given in Tables 1 and 2 it is apparent that this reactor is capable of producing very short periods. The excess reactivity requirements are the maximum values expected and may be somewhat smaller in practice; however, the control system should be designed to take care of extreme conditions that may be realized. In normal operation every effort should be made to see that the excess reactivity of the reactor is held to the minimum consistent with satisfactory performance.

TABLE 2—Reactivity Allowed for Losses under Normal Conditions

Reactivity requirements	ρ
Operational requirements	0.003
Temperature effects	0.00375
Fuel depletion + misc. fission products	0.0015
Xenon poisoning	0.0045
Required for operation	0.01275
Allowance for experiments (To be obtained through fuel addition at time experimental facility is installed)	0.02

Safety Rods

The safety rods should have a control effect of several times the maximum excess reactivity the reactor has built into it. In this reactor, the method of control selected was the introduction of adjustable poison rods into the active core. These rods contain boron which has a large neutron-absorbtion cross section. Their presence reduces reactivity by absorbing neutrons, some fraction of which would otherwise have been absorbed in a fission reaction. There are two such rods, each being equivalent to $\rho = -0.05$ when inserted.

Control Rod

A control rod of limited effectiveness is provided; this rod can change k_{eff} by approximately 0.005. Manual control of this rod enables the operator to adjust the neutron flux level. However, the primary reason for including this control rod is the desirability of incorporating an automatic level control system. Possible failure of this automatic control system, resulting in complete rod withdrawal, dictated that the rod have limited effectiveness so that dangerously short periods would not occur due to such a failure.

Safety Circuits

The safety system for this reactor must provide a large part of the protection against operational hazards. The dangers involved are:

1. The power level of the reactor may rise to such high levels that the shielding is no longer adequate for protection of personnel from radiation.
2. The power may rise to such a high level that the heat transfer system will allow the fuel plates to melt or vaporize, thus damaging the reactor and releasing fission products which would contaminate the water in the pool and the air around it and thereby constitute a radiation hazard to personnel.
3. Personnel may be subjected to radiation arising from an unshielded experimental hole leading to the reactor or from an irradiated object being withdrawn from the reactor without sufficient shielding.
4. The pool may be drained, thus exposing personnel to a source of radiation.

The first two possibilities constitute the hazards to be discussed here. The third will be considered as coming under a discussion of health physics protection and the fourth as being part of the over-all reactor facility design; both of these may be coupled into the control system as will be shown later.

It has been experimentally shown that if the power level rises to more than a few hundred kw, the reactor will boil, and steam will displace sufficient moderator to inhibit runaway (*2*). A qualification on the foregoing statement is that the rate of rise of power in the experiment was very low and therefore not conclusive as to the behavior under conditions of a very rapid rise.

Calculations have been made to determine the kinetic behavior of this reactor after an arbitrary stepwise increase in k_{eff} of 2% above prompt critical (*3*). The resulting maximum fuel-plate temperature was calculated to be 390° F, the critical condition persisting until approximately 10% of the moderator has been expelled by steam; the time at which the reactor becomes subcritical was found to be 0.127 sec. This calculation is not conclusive due to lack of information on transient boiling heat transfer and rate of formation of steam bubbles, but the situation appears to be reasonably satisfactory.

Safety system design. The design of the safety system is dictated by possible reactor kinetic behavior and previous experience. The safety system should manifest itself as little as possible in normal operation in order that there should be no desire to modify the system in such a way as to render it less effective.

The safety system, Fig. 1, is arranged to shut down the reactor when neutron flux levels rise to a point indicating an overload of approximately 30%. This shutdown is accomplished by reducing the currents supplied to electromagnets supporting the safety rods (*2*, Fig. 3) which then fall into special reactor fuel elements under the influence of grav-

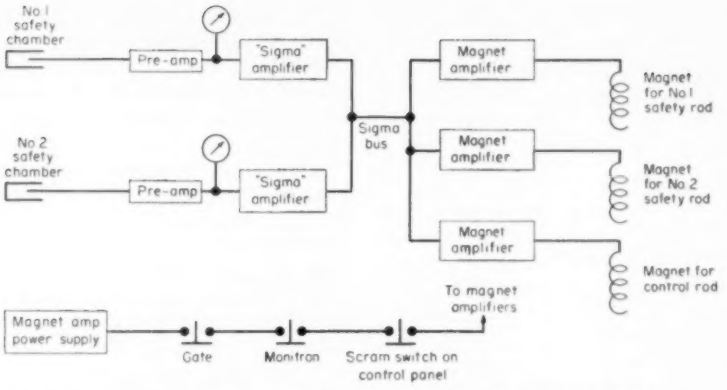


FIG. 1. Safety and control rod circuits. Chambers indicate neutron-flux level

ity. An iron armature is fastened to the top of each rod, and means are provided to dissipate the kinetic energy when the rod reaches the end of its fall.

The electromagnets which support the safety rods are made from one piece of Armco soft iron in an iron-clad design. The exciting coil is impregnated under vacuum, after assembly in the magnet, with Harvel "Oil Stop." This forms a waterproof and shock-absorbing bulk insulator around the coil. Tests have shown this material to be stable under the neutron and gamma irradiation expected at the location of the magnets.

The magnets were designed to support the rods with an air gap of 0.005 in. when 30 ma of exciting current flows in the winding. The air gap is obtained by crowning the face of the armature; this crowning also makes perfect alignment between magnet and armature face unnecessary. Tests indicate that the release time, with 50% more current than is necessary to hold the rods, is less than 40 msec when a step-function input signal is applied. The actual release time after the reactor passes the level at which release is desired is much less than this for reasons which will be discussed later.

The signal proportional to neutron flux is obtained from a boron-coated ionization chamber (*2*, Fig. 3). This chamber produces an output current of about 10^{-5} amperes when exposed to a thermal flux of 2.5×10^9 neutrons/cm²/sec. With 300 volts applied to the electrodes, the relation between neutron flux and current is linear up to approximately 10^{-4} amperes. A large voltage signal minimizes the problems concerned with d-c amplifier operation. A signal of approximately 10 volts at full power with a chamber current of 3×10^{-5} amperes requires a resistor of 3.3×10^5 ohms. The *RC* time constant of this resistor and the chamber and cable capacitance is 0.0006 sec, small enough to be negligible in this application.

Magnet current control. The amplifiers supplying current to the magnets are controlled by a mixing circuit. The output of the preamplifier from a cathode follower is fed into the mixer, which accepts signals from several sources. The mixer operates in such a way as to produce an output signal which is nearly constant until the reactor approaches full power and then becomes proportional to the largest signal applied to the mixers.

In operation, the magnet current can be set to release the magnet when a certain flux is reached. As the power level of the reactor is increased, the magnet current remains nearly constant until the reactor approaches full power. The current is then decreased as the flux increases until the point is reached where the magnet is no longer able to support the rod.

The current which the output tubes supply to the magnet is furnished by a separate transformer. Control of the voltage applied to this transformer provides a convenient method of introducing manual shutdown signals, safety interlocks, etc.

The time response of the system from chamber to safety rods can be calculated with the aid of experimentally determined quantities. Measurements show that this system is capable of releasing the rod in less than 0.04 sec after the shutdown level is exceeded. The length of time after release for the rods to decrease k_{eff} by 0.01 would be approximately 0.13 sec. The rate at which k is increased by withdrawal of the rods should be limited to insure that the reactor can be shut down by the safety system without causing an overexposure to personnel or damage to the reactor.

Calculations have been made based on a linear increase of k_{eff} caused by complete rod withdrawal in 8 min. The results show that if a flux of 1 neutron/cm²/sec is present in the reactor at the time rod withdrawal starts, the reactor period would be longer than 0.06 sec when the flux level exceeds the safety shutdown point. If the reactor is assumed to rise on a period of 0.06 sec during the entire time required for the safety rods to decrease k_{eff} by 0.01, the maximum level attained would be approximately 20 times the safety shutdown level. The flux would then fall rapidly as the rods decreased k_{eff} still further. This overload would not be serious since the duration would be short. A source sufficiently strong to produce a flux of 1 neutron/cm²/sec is easily obtainable and should be built into the reactor.

Operating Instruments

The instruments necessary for observation of the reactor level, as determined by flux, must cover the entire range of expected fluxes. For this reactor, the range to be covered is approximately 3×10^{10}. Figure 2 is a block diagram of the operating instruments.

Start-up. Due to the intense gamma activity resulting from previous operation, the measurement of neutron flux during start-up must be done by an instrument which discriminates strongly in favor of the signals produced by neutron reactions in the detector. Such a device is the U^{235} fission chamber when used as a pulse-type chamber followed by a linear amplifier and pulse-height selector (*9*).

The size of the pulses produced when fission occurs in the chamber is much greater than the size of pulses produced by the gamma interactions in the chamber material or by the alpha emission of the uranium. The output of the pulse-height selector, set to transmit only pulses resulting from fission, is fed to a log-count-rate meter, to obtain a signal proportional to the logarithm of the counting rate from 1 cps to 10^4 cps. This signal is recorded on a strip chart recorder for graphic presentation.

The fission chamber is movable and

therefore may be used to cover the entire range of operation by changing the position and taking advantage of the attenuation of the neutron flux in the water. This channel gives little trouble; however, the accuracy of the log-count-rate meter is limited to about ±10% for routine use. A scaler and timer are provided so that quantitative measurements of the counting rate may be made and so that the low counting rates encountered during initial phases of reactor loading may be observed. The scaler is connected to the output of the pulse-height selector.

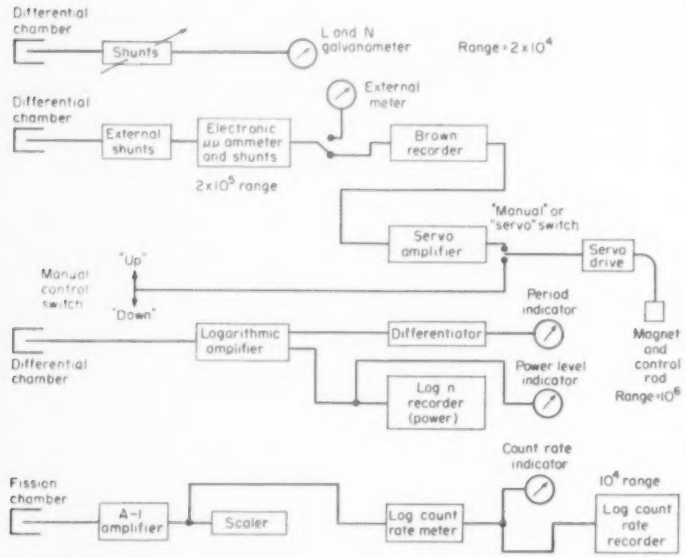


FIG. 2. Operating instruments for accurate flux indication, period and power-level indication, and start-up flux indication

Normal operation. During normal operation, it is convenient to use a chamber which produces a direct current proportional to the neutron flux, such as a compensated ion chamber. This chamber has two sensitive volumes, one coated with boron, the other not coated. The boron-coated region is sensitive to both gamma radiation and to neutron radiation; the uncoated region is sensitive to gamma radiation only. The gamma signal can be subtracted from the neutron-plus-gamma signal, leaving a signal proportional to the neutron flux plus any error resulting from the difference between the two gamma signals.

This chamber produces a current of about 10^{-4} ampere when exposed to a thermal-neutron flux of 10^{10} neutrons/cm²/sec. In this reactor, the compensated chamber provides a current proportional to the neutron flux at the chamber over a range of about 10^6; over a range of nearly 10^5, the current can be relied on to be proportional to the flux to within about 1%.

Pile period and power level. A compensated chamber is connected to a pile-period meter in which the chamber current is passed through a thermionic diode (9004). The voltage across the diode is proportional to the logarithm of the current passing through the diode over a range of 10^6 or greater. The log signal is amplified and recorded to provide a record of the pile power level. The amplified signal is also passed through an *RC* differentiator producing a signal inversely proportional to the pile period. A period signal can be transmitted to the safety system through the mixer circuit so that the reactor will be shut down if unnecessarily short periods are realized. Interlocks can also be arranged so that permission to withdraw the rods is taken away when periods faster than necessary for normal operation are encountered.

The pile-period meter is an extremely valuable operating instrument as it gives information on the flux level and reactor period over the range from 10^{-6} of full power to full power without changing any range switches. However, this channel, like the log-count-rate meter channel, is not a highly accurate indicator of flux level due to potential drifts in the thermionic diode.

Accurate flux determination. The accurate determination of neutron flux can be accomplished by an instrument which accurately indicates the current from a compensated ion chamber. One instrument, which has proven to be accurate and dependable, is the Leeds and Northrup, Model 9836A, stabilized micromicroampere amplifier. This instrument, as delivered by L. & N., covers the range from 10^{-9} amperes, full scale, to 2×10^{-6} amperes, full scale. The addition of an external shunt with a current division ratio of 100 and a switch to insert the shunt will extend the range to 2×10^{-4} amperes, full scale. This channel will then cover a range of 10^5 in reactor power within an accuracy of 1%. The signal is recorded on a strip-chart recorder, thus providing an easily read scale and a record which can be used to check on reactor operation after the completion of an experiment.

A galvanometer and shunt can be used to read the current from a separate compensated chamber, as a check on the electronic channel. Experience indicates that the L. & N. amplifier gives very little trouble and its indication has always agreed with the galvanometer.

The Control Circuits

The control circuits are designed in such manner as to enable easy operation of the reactor, with interlocks to protect the equipment and provide certain safeguards against possibly dangerous situations.

The magnet power is supplied, through vacuum tubes, by transformers fed from a control line. This line can be deenergized by a number of switch and relay contacts. Representative of these are contacts on the gates leading to the reactor bridge, manual shutdown switches located on the console and at convenient locations around the pool, and contacts located in health-physics monitrons mounted above the surface of the pool on the reactor bridge. In addition, interlocks should be arranged so that any movement of experiments which might affect the reactivity would cause a shutdown.

The safety rods are driven by a-c motors, controlled from the operating panel. Limit switches are provided to stop the motors at the upper and lower positions of the rods. These motors are interlocked so that the rods cannot be raised unless the log-count-rate recorder is indicating at least 1½ cps. This provides a partial check on the operation of the fission-chamber circuit and assures the presence of a neutron source. During startup, the safety rods cannot be withdrawn unless the control rod is fully inserted. The control rod cannot be withdrawn unless the safety rods are at least three-fourths withdrawn, thus insuring that 6% to 8% negative reactivity is available when withdrawing the control rod. Synchro transmitters and receivers are used to indicate the position of the drive mechanisms for the rods.

The position of the fission chamber can be changed by a motor controlled from the operating panel; pilot lights indicate when the chamber reaches the limits of its travel.

Automatic Level Control

The desirability of maintaining the reactor flux within limits of ±1%, over extended periods of time, indicates that a servo system should be included. One servo proposed for the low-cost research reactor consists of a two-phase control motor driven by an electronic amplifier. The input for this amplifier is generated by a synchro generator and a synchro-control transformer. The synchro-control transformer is coupled to the recorder driven by the L. & N. amplifier; the position of the shaft of the synchro generator is set by hand. The circuit is arranged so that zero rod motion is obtained when the recorder indicates the desired level. The servo has rate feedback from a tachometer coupled to the control motor to provide the necessary damping.

A transfer switch is provided on the control panel for changing from manual to automatic control. In operation, the reactor is brought to the desired level under manual control; then the servo is brought into operation by switching to automatic control. Small changes in level may be made by resetting the synchro generator which provides the desired level signal. An adjustment knob is located on the front of the recorder for this purpose, and a pointer provided on the recorder scale for indicating the desired level.

Higher Power Operation

For operation at power levels up to one megawatt (*2*), the control system would remain basically the same. However, the increased reactivity requirements would indicate some changes. A change from two to three safety rods is desired to maintain the safety shutdown margin. Withdrawal of the rods should be limited by the reactor period, and safety shutdown should be actuated by reactor period in addition to shutdown on excess level. Action should be taken to insure that reactor operation is coordinated with the operation of the forced circulation cooling; this can be done through the interlock system.

* * *

Many members of the ORNL staff contributed to the design and construction of the control and safety system currently in use. Some of the major contributors are: P. R. Bell, E. P. Epler, J. C. Gundlach, S. H. Hanauer, W. H. Jordan, H. W. Newson, and J. E. Owens.

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Sorbed Gases and High-Vacuum Systems

LIBERATION of absorbed, occluded, and adsorbed gases from metals or glass can cause "leakage" in high-vacuum systems where extraneous gases must be excluded. Measurements made by engineers at Sam Tour & Co., Inc., New York, indicate that up to 17 cm^3 of gas, predominantly hydrogen, can be trapped in 100 grams of aluminum during casting.

Gas permeability measurements were made during testing of the effectiveness of a plastic impregnant for decreasing the porosity of aluminum castings. Adsorbed and absorbed gases caused a discrepancy in results obtained by two methods.

In the first method, one side of a cast plate was subjected to a vacuum of about 10 microns of mercury while the other side was at atmospheric pressure. The rate of increase in pressure in the evacuated system, which had a known volume, was used as a measure of leakage. Leakage rates of 1×10^{-7} $ft^3/in^2/hr$ were indicated.

In the second method, one side of the plate was again subjected to high vacuum, but the other side was exposed to an atmosphere of helium. A helium leak detector was used in the evacuated system to measure leakage. No leakage was detected, however.

The apparent leakage found with the first measurement was traced to gases occluded or absorbed during casting of the metal and to gases adsorbed on metal surfaces exposed to air. When the metal is subjected to vacuum, the gases are liberated at varying rates. This release of gases is accelerated by even a slight increase in temperature; the rate of liberation increases exponentially with temperature rise. This release of gases affected the pressure measurements, but the helium measurements were not changed.

Absorbed and adsorbed gas will be found in and on many metals, while adsorbed gases will be found on glass. It is, therefore, important to degassify these materials before their use in a high-vacuum system. These systems can be purged by subjecting them to high vacuum and to temperatures of several hundred degrees.

Shaped Sources for Teletherapy Units

The idea of distorting teletherapy-source shapes to give a greater surface area per unit volume is discussed and shown to be impractical. A disk-shaped source offers the greatest efficiency

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ONE OF THE limiting factors in designing teletherapy units with radioisotope sources is the attainable volume specific activity. The mass specific activity of europium-152,154 and cobalt-60 is limited by reactor time and flux. The maximum obtainable mass specific activity of cesium-137 in the form of the sulfate is about 23 curies per gram. By compression, Cs^{137} in this chemical form can be brought to a volume specific activity of about 95 curies per cm^3. $Eu^{152,154}$ and Co^{60} can be pushed much higher, but self-absorption markedly reduces their efficiency.

It has been suggested repeatedly that the efficiency of the sources could be greatly improved by distorting their shape to give a greater surface area per unit volume. We have concluded that this is impossible for the reasons given in the following discussion.

The Basic Design

Assuming that a unisource unit only is being discussed, the basic features of the design of any unit will be a source of activity enclosed within a shield with some mechanism for turning the beam on and off as illustrated in Fig. 1. There must also be some form of collimating cone. Diaphragms or beam-limiting devices would necessarily be added somewhere in the collimating cone.

The Presenting Face

If a beam with fixed cross section is desired, then the presenting shape of the face of the source should be that of the desired beam. If more than one beam cross section is to be used, as is true in most cases, the cross section of the source should be that best fitting all shapes. Since penumbra is one of the limiting factors of source diameter, the shape giving the greatest area for the least diameter would also give the greatest volume for the least penumbra. This is found in a circular cross section which fits the demand for any configuration of beam-limiting device.

Therefore, it has been accepted that a circular cross section is most efficient for any unisource unit.

The simplest circular cross section source would be a right cylinder.

Possible shapes of the presenting face. The question has been raised concerning the use of shaped sources. For example, a cone with its apex in the presenting face has a greater presenting surface area and might, therefore, impose less self-absorption in its depth and, hence, yield a greater intensity of useful radiation. If the apex of a cone or other shaped source is fixed at a height equal to the radius of the cross section, i.e., 1.5 cm, then the area of a circle would be 2.25π, a right cone would be 3.21π, a paraboloid 3.75π, a hemisphere 4.50π. This progression would continue as the hemispheroid became more oblate until it approached the shape of a right cylinder moved 1.5 cm down the collimating cone.

The surface area of the face of a hemisphere is twice that of a flat circle. It can be used as the type example.

Volume at Which Sphere and Right Cylinder are Equal with Fixed Presenting Face Diameter

Diameter of source (cm)	*Volume of a sphere (cm^3)*	*Height of a right cylinder which would give equal volume (cm)*	*Curies in source when volume of cylinder equals sphere*	*% of intensity reduced by self-absorption for given diameter of*	
				Cylinder	*Sphere*
1	0.52	0.66	40	7	8
2	4.19	1.33	322	14	15
3	14.14	2.00	1,089	20	22
4	33.51	2.67	2,580	26	28
5	65.45	3.33	5,040	30	32

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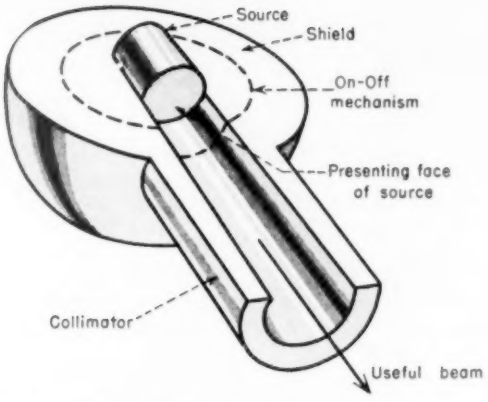

FIG. 1. Basic design of any unisource teletherapy unit

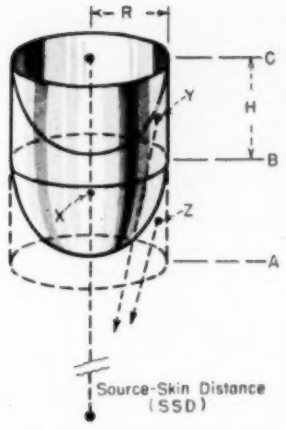

FIG. 2. Hemispherical-cup-shaped source with a disk source of equal volume

The argument holds true to a greater or lesser extent for any other shape.

Cup vs Right Cylinder

If a hemisphere were to be used, then the diameter of the source would fix a maximum volume. However, if a hemispherical surface is extended in height to match the shape of a right cylinder, the volume is unlimited. Therefore, the hemispherical cup, as shown in Fig. 2, should be the figure to compare with a right cylinder. A large number of parameters are affected when the shape of the source face is changed, i.e., the source-skin distance, the radiation intensity over the field, the penumbra, the volume of material in the source, self-absorption factors, etc. A number of simplifying factors must be introduced before the problem can be analyzed.

To keep a reasonably flat radiation field at the source-skin distance, assume that the SSD is between 50 to 100 cm and only about a 5% to 10% variation over the cross section is desirable. Assuming that only the parallel primary photons are measured, then the greatest possible variation in SSD allowable can be derived from the inverse square law. At 3-cm variation between points A and B in Fig. 2, there is about a 6% variation in the inverse-square factor at 100 cm and about 13% at 50 cm. At a 5-cm variation, this factor will more than double. Hence, we can fix a maximum source diameter at about 3 cm. The argument will hold true for any diameter, but can be calculated more easily at one fixed diameter. If we accept a radius of 1.5 cm (points A–B) and a source depth (points B–C) of 1.5 cm, then the volume of the hemispherical cup is the same as that of a right cylinder of radius = height = 1.5 cm.

Since the SSD is long compared with the A–B distance (the depth of the source), the presenting face, no matter what its shape, is effectively a circle and the effective presenting area is πr^2. This argument breaks down at very short distances.

The source volume is always identical in any shape of cup if r is equal to or greater than h, and this volume is equal to that of a right cylinder. If the volume is going to be very much less than $\pi r^2 h$, then shaping of sources will allow for a decreased self-absorption and a more efficient usage of the source material. The table nearby shows that such small volumes are useless for teletherapy units. The problem of teletherapy at any reasonable diameter will demand over 10 roentgens per minute at one-meter SSD, and such sources are bound to have $h > r$ with the expected specific activity of Cs^{137}. It is shown later that this argument does not break down even with Co^{60} or $Eu^{152,154}$, where specific activities over 100 curies per gram could be produced.

If the volume of a hemispherical cup and a right cylinder source are about equal, then the attenuation due to distance and self-absorption are the same from point X in Fig. 2. Since the most forward point defines the limits of the closing device on a machine, a right cylinder source comparable to the hemispherical cup could be placed at A–B. This means that radiation from point Y has significant attenuation both from self-absorption and distance in a hemispherical cup. All of the radiation from the most effective portion of the forward edge of a right cylinder at point Z is lost in a hemispherical cup or any other shaped source.

If the source volume is small enough and there is no preferred direction of radiation, then a sphere would be the best shape, since the volume to total integral linear dimension ratio is optimum. The table gives a definition for "small enough" for each diameter from 1 to 5 cm.

To illustrate the interpretation of the table, if a 3-cm diameter presenting face is allowed, then it is possible to use a sphere with about 14 cm^3 volume. This would contain a maximum of 1,089 curies of Cs^{137}. A right cylinder of the same diameter would be 2 cm high. There would actually be 2% less self-absorption from the cylinder than from the sphere when the radiation has a preferred direction and is collimated.

Since the same self-absorption function holds for ellipsoids, the sphere stretched in an axis perpendicular to the presenting face, without change in the diameter of the presenting face, results in a volume increase having no more efficiency than that of a right cylinder. If a parabola or a right cone is stretched so that its apex came closer to the skin, there is an obvious increase in intensity especially when the stretching reaches a point where h is much less than r with any fixed volume. How-

ever, at this point, there is no longer a collimated beam if SSD is kept at or below 100 cm.

Therefore, it seems obvious that the right cylinder with the base as a presenting face is the most efficient source shape for a teletherapy unit.

General Solution

A more general solution can be derived mathematically for a source of any given shape. We consider first a source such as that shown in Fig. 3. The source is taken to have a fixed given volume V and to consist of material of specific activity a expressed in curies per cm³. The total radiation emitted from the source per second is denoted by S and is given by

$$S = kaV$$

where k is a constant, characteristic of the radioisotope of which the source is made. S could be expressed in terms of photons emitted by the source per second, or it could be expressed in roentgens per second.

Let the source have a radius R and the collimating tube have a constant cross section of this same radius and length L, as shown in Fig. 3. Then, a point source placed at the origin O of source strength S would subtend a solid angle at the collimator portal of

$$\Omega = \frac{\pi R^2}{L^2}$$

and the radiation I leaving the collimator portal will be

$$I = S\frac{\Omega}{4\pi} = S\left(\frac{R}{2L}\right)^2 \qquad (1)$$

For an extended source of any given shape, the portion of the total radiation emitted from the source which passes through the collimator portal will differ from that for a point source by a factor f which depends on the size and shape of the source and the collimator distance L, such that for this source

$$I = S\left(\frac{R}{2L}\right)^2 f \qquad (2)$$

It is our purpose to evaluate the factor f for sources which all have the same volume V and total activity S but are made in various shapes. It will be convenient to compare the value of f for each shape with the comparable value f_0 for a disk-shaped source of radius R and thickness b which is taken as a standard. The volume of the standard source is

$$V = \pi R^2 b$$

and all other shaped sources will be adjusted to have this volume.

All sources here considered are taken to have axial symmetry about the collimator axis. We introduce cylindrical coordinates ρ, φ, z and let the surface of the source be defined by $\rho = r = r(z)$ where r is a function of z. The point on the source nearest the collimator portal is taken at the origin of coordinates, O. The volume of that part of the source lying below a given plane z is given by

$$\tau = \tau(z) = \int_0^z dz \int_0^r 2\pi\rho d\rho = \pi \int_0^z r^2 dz \qquad (3)$$

The total volume of the source is then

$$V = \tau(B) = \pi R^2 b \qquad (4)$$

where B is the depth of the source along axis z as seen in Fig. 4. It is convenient to introduce the dimensionless quantities x, y, β and ν as follows

$$r = xR,\ z = yb,\ B = \beta b,\ \tau = \nu V$$

or

$$\tau(z) = \pi R^2 b\nu(y) \qquad (5)$$

We find then

$$\nu(y) = \int_0^y x^2 dy \qquad (6)$$

$$\nu(\beta) = 1$$

The volume element $d\tau$ has a radiation strength $(S/V)d\tau$ and subtends the solid angle at the collimator portal

$$\Omega = \frac{\pi R^2 \cos\theta}{(L+z)^2 + \rho^2} = \frac{\pi R^2 (L+z)}{[(L+z)^2 + \rho^2]^{3/2}}$$

Thus the radiation admitted through the collimator portal is

$$I = \frac{S}{V}\int \frac{\Omega}{4\pi} d\tau$$

and the factor f is given by

$$f = \frac{L^2}{\pi R^2 V}\int \Omega d\tau \qquad (7)$$

Introducing the expression for Ω, this becomes

$$f = \frac{L^2}{V}\int_0^B (L+z)dz \times \int_0^r \frac{2\pi\rho d\rho}{[(L+z)^2+\rho^2]^{3/2}}$$

$$= \frac{2\pi L^2}{V} \times \int_0^B \left[1 - \frac{1}{\sqrt{1 + \left(\frac{r}{L+z}\right)^2}}\right] dz$$

Expanding the integral and neglecting terms in $(z/L)^2$, this becomes

$$f = \frac{\pi}{V}\int_0^B r^2\left(1 - 2\frac{z}{L}\right) dz$$

Transforming to variables x, y, and ν by Eq. 5 and using Eq. 6, this becomes

$$f = 1 - (2b/L)\int_0^\beta x^2 y dy$$

or, on integrating by parts

$$f = 1 - (2b/L)\left[\beta - \int_0^\beta \nu(y)dy\right]$$

For a disk, $\beta = 1$ and $\nu(y) = y$. Thus

$$f_0 = 1 - b/L \qquad (8)$$

A family of source shapes of a given type may be obtained by choosing

$$x = (y/\beta)^n \qquad (9)$$

for which $n = 0$ = a right cylinder or disk, $n = \frac{1}{2}$ = paraboloid, and $n = 1$ = cone. For such sources

$$\nu(y) = \int_0^y x^2 dy = y^{2n+1}/(2n+1)\beta^{2n}$$

and the condition of Eq. 6 gives

$$\beta = 2n + 1$$

so that $\beta = 2$ for the paraboloid and $\beta = 3$ for a cone.

For such sources we find

$$\int_0^\beta \nu(y)dy = \frac{2n+1}{2n+2}$$

so that

$$f = 1 - \frac{(2n+1)^2}{n+1}\frac{b}{L} \qquad (10)$$

and is thus smaller for all sources (all $n > 0$) than its value for a disk. Thus the disk gives the best shape.

In all of the preceding calculations, the radiation from each volume element $d\tau$ in the source is regarded as contributing its full intensity to the radiation leaving the collimator portal. This means that the source material is regarded as being completely transparent to the radiation and, thus, self-absorption has been neglected. If, however, self-absorption is important, as it usually is, deep-lying portions of

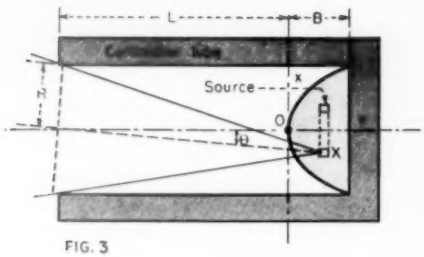

FIG. 3

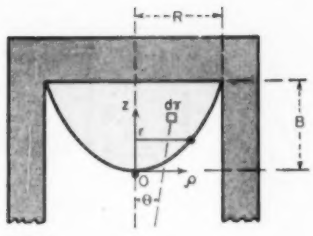

FIG. 4

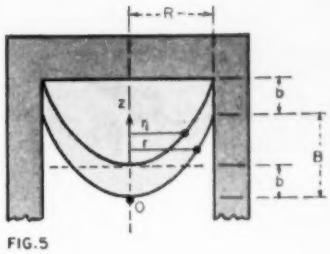

FIG. 5

EFFECT of source shape on intensity

the source, such as those in the neighborhood of $z = B$, $\rho = 0$ in Fig. 4, will contribute very little to the portal radiation because of severe attenuation in passing through the intervening source material.

To take self-absorption into account properly, radiation strength $(S/V)d\tau$ of each volume element should be multiplied by an attenuation factor

$$e^{-u[y-y(r)]} \qquad (11)$$

where $y(r)$ is the inverse of the function $r(y)$. This, however, not only involves extensive mathematical complexity but does not lead to particularly useful results. The reason is that, since with self-absorption deep-lying portions of the source are largely wasted, it is much better to remove them and redistribute the source material so that none of it lies deeper than a preassigned axial distance from the front surface of the source. This can be done by simply translating the surface $r = r(z)$ in Fig. 4 a distance b along z to produce an "interior" source surface

$$r = r_i(z) = r(z - b) \qquad (12)$$

as shown in Fig. 5. This makes the z-dimension of the source at each value of ρ the same and provides all annular sections with the same average attenuation factor (Eq. 11). Thus, the attenuation can be incorporated in the source strength S and the calculation carried out without explicit use of a self-absorption factor.

The source now divides itself into three regions

(1) $0 \leq z < b$, ρ varies from 0 to r
(2) $b \leq z < B$, ρ varies from r_i to r
(3) $B \leq z < B + b$, ρ varies from r_i to R

It is convenient to retain the function $\tau(z)$ as defined by Eq. 3. The value of τ for $z = B$ is now, however, no longer equal to the volume V of the source so that Eq. 4 no longer holds. To find the volume of the source, we have contributions from each of the above three regions as follows

$$\begin{aligned} V &= \int_0^b dz \int_0^r 2\pi\rho d\rho + \int^B dz \times \\ &\quad \int_{r_i}^r 2\pi\rho d\rho + \int_B^{B+b} dz \int_i^R 2\pi\rho d\rho \\ &= \pi \int_0^B r^2 dz - \pi \int_b^{B+b} r_i^2 dz \\ &\quad + \pi R^2 \int_B^{B+b} dz \\ &= \pi R^2 b \end{aligned}$$

where we have used Eq. 12 and a change of coordinates to $z = u + b$ in the second integral to show that the second integral reduces to the first so that their difference vanishes. Thus the volume of any source of this shape and character is the same as that of a disk of the same axial thickness.

If we now evaluate Eq. 7 for the three regions mentioned, we find

$$\begin{aligned} f = \frac{2\pi L^2}{V} \times & \left\{ \int_0^b \left[1 - \frac{1}{\sqrt{1 + \left(\frac{r}{L+z}\right)^2}} \right] dz \right. \\ & + \int_b^B \left[\frac{1}{\sqrt{1 + \left(\frac{r_i}{L+z}\right)^2}} - \frac{1}{\sqrt{1 + \left(\frac{r}{L+z}\right)^2}} \right] dz \\ & \left. + \int_B^{B+b} \left[\frac{1}{\sqrt{1 + \left(\frac{r_i}{L+z}\right)^2}} - \frac{1}{\sqrt{1 + \left(\frac{R}{L+z}\right)^2}} \right] dz \right\} \end{aligned}$$

Expanding the integrals as before and neglecting all terms in $1/L^2$, we obtain

$$\begin{aligned} f = \frac{\pi}{V} \left\{ \int_0^B r^2 \left(1 - 2\frac{z}{L}\right) dz \right. \\ - \int_b^{B+b} r_i^2 \left(1 - 2\frac{z}{L}\right) dz \\ \left. + \int_B^{B+b} R^2 \left(1 - 2\frac{z}{L}\right) dz \right\} \end{aligned}$$

Again using Eq. 12 and the transformation $u = z - b$ in the second integral, this becomes

$$\begin{aligned} f = \frac{\pi}{V} \left\{ 2\frac{b}{L} \int_0^B r^2 du \right. \\ \left. + R^2 \left(b - \frac{2Bb + b^2}{L} \right) \right\} \end{aligned}$$

Finally using Eq. 5 and $V = \pi R^2 b$, we obtain

$$f = 1 - \{1 + 2[\beta - \nu(\beta)]\} \frac{b}{L} \qquad (13)$$

This equation is entirely general and holds for any shape source that satisfies the conditions specified in Fig. 5. For the particular family of sources specified by Eq. 9, we have

$$\nu(\beta) = \beta/(2n + 1)$$

so that

$$f = 1 - \left(1 + \frac{4n\beta}{2n + 1}\right) \frac{b}{L} \qquad (14)$$

Again it can be seen that the largest factor f is obtained for any given b/L with a disk for which $n = 0$, and Eq. 14 reduces to Eq. 8.

Thus, under either of the conditions considered here, the disk-shaped source gives maximum radiation at the collimator portal. For such a source, the amount of radiation leaving the portal is given by combining Eqs. 2 and 8 as $I = S(R/2L)^2(1 - b/L)$. END

High-Energy Nuclear Physics

In attempting to understand the nature of the physical world, man has uncovered a wealth of data. Among the most confusing of these data are the results of high-energy experiments, particularly the many new particles that have been found. This is a summary of the highlights of a conference whose aim was to try to find some pattern in the morass of data and discoveries

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THE PROBLEMS of understanding the phenomena that are apparent in experiments performed at high energies was the subject of the Third Annual Conference on high-energy physics held at the University of Rochester, Dec. 18–20, 1952.

The conference was jointly sponsored by the Department of Physics of the University of Rochester and by the National Science Foundation. It was attended by approximately 150 physicists currently active in nuclear, high-energy, and cosmic-ray research.

This conference matched, if it did not exceed, its predecessors in the excellence of its organization and in the warmth of the hospitality of its hosts, and no report, however technical, would be complete without an acknowledgment of indebtedness to the members of the physics department of the University of Rochester, and especially to its chairman, Robert E. Marshak.

This summary is intended to represent this writer's impressions of those aspects of the conference which appear to him to represent the most significant or interesting recent developments in the fields discussed. No attempt will be made at completeness of coverage, nor will any effort be made to present all of the experimental details and arguments which were advanced in favor of the conclusions stated.

Since the work of many investigators was reported, it would be impossible to give adequate credits in such a summary. We have, therefore, resorted to the expedient, in most cases, of crediting work to the laboratory of its origin.

On the theoretical side, the main progress of the last year seems to have been of a psychological nature—improved morale. A new optimism and confidence in the potentialities of meson field theories pervaded the air of the theoretical sessions; and, even if it was sometimes difficult to discern the factual bases for this optimism, its presence gave to the theoretical sessions an entirely new aspect as compared to the gloomy "wakes" over meson theory held in past years.

The theoretician who has, more than any other, led the movement for the "new look" at meson theory is M. M. Lévy, and perhaps the outstanding feature of his contribution is that he has been willing to take the results of meson theory more seriously than did his predecessors. Equally significant is the fact that he has carried the calculations further than had been previously achieved and has derived a nuclear potential—the "Lévy potential"—which, in the low-energy limit, is in substantial agreement with the known features of the nucleon-nucleon interaction (*1*). Preliminary results of meson-theoretic calculations on meson-nucleon scattering (mainly by G. F. Chew, F. J. Dyson, H. A. Bethe and their co-workers) also appear to show some promise of agreement with observation.

On the experimental side, the field of high-energy research, both with accelerators and with cosmic rays, has been marked by a great deal of careful experimentation aimed, on the one hand, at elucidation of the nature of the fundamental interactions involving mesons and nucleons and, on the other hand, at establishing the existence and the properties of the many new unstable particles which have come into being in recent years.

As a result, although there have been no spectacular new discoveries, a good start seems to have been made in bringing some order into the field. Although there is, unfortunately, no assurance that the number of heavy unstable particles is finite, the conference gave, at least, some indications that we may achieve a measure of understanding of the available observations before the cosmotron and its

contemplated followers start to pour their discoveries into the already overflowing stream.

Finally, some experiments at Columbia and Rochester were reported which indicate that the μ- and π-mesons, at least, are well on the way towards becoming accepted members of the old-established, respected family of "fundamental" particles. These were observations on mesic X-rays, emitted when the meson is captured into an atomic orbit and proceeds toward the K-shell, radiating as it goes.

The possibility of applying spectroscopic techniques (albeit of an unconventional nature) to mesic atoms signifies the beginning of precision measurements on the static properties of these mesons. Although the next important step, the study of the meson-hydrogen atom (mesonium), has not yet been achieved, results reported indicate that it cannot be too far off.

THEORY OF NUCLEAR FORCES

The conference began with a discussion of the nature of the forces that act between nucleons.

Isotopic-Spin Selection Rules

The first part of this session was devoted to a discussion of the evidence for, and consequences of, the charge-independence of nuclear forces. By charge-independence is meant the equality of the nuclear neutron-neutron, neutron-proton, and proton-proton forces in the same states. Most of this evidence derives from low-energy data on the nucleon-nucleon interactions and on the properties of the low-lying energy levels of light nuclei. The evidence is, on the whole, indicative of a large measure of charge-independence; the real question is the (small) extent of the deviations from charge-independence, their causes and consequences.

To the extent that nuclear forces are truly charge-independent, neutrons and protons may be considered as the two possible states of a single particle, the nucleon. For convenience, we can imagine a special "charge space," in which the nucleon has two possible orientations, corresponding to proton or neutron. Formally, this situation is completely analagous to the description of spin in ordinary space.

Indeed, this formal analogy can be carried out completely by ascribing to the nucleon an "isotopic spin," or I-spin, $\tau = \frac{1}{2}$. The two possible orientations of the I-spin, $\tau_z = +\frac{1}{2}$ or $-\frac{1}{2}$, correspond, respectively, to the proton and the neutron. In considering systems containing two or more nucleons, the I-spins combine, exactly as do ordinary angular-momentum vectors, to yield a total isotopic spin vector, $\mathbf{T} = \Sigma\boldsymbol{\tau}_i$, and a total z-component, $T_z = \Sigma\tau_{iz}$, which is a measure of the excess of protons over neutrons.

In addition to the fact that the I-spins combine according to the quantum mechanical rules governing angular momentum, the system must obey a generalized Pauli exclusion principle for nucleons, which requires that no two nucleons may have the same set of quantum numbers (which set includes the values of τ_z).

The advantage of such an approach is that the assumption of charge-independence of nuclear forces imposes certain selection rules on the isotopic-spin change in nuclear reactions. The past year has seen the beginnings of a careful examination, both experimental and theoretical, of the degree to which these selection rules are obeyed. However, these selection rules are, at best, only approximate, since the forces between nucleons cannot be absolutely charge-independent, even if the strictly nuclear part of these forces were.

Thus, the electromagnetic forces between protons are different than those between neutrons; in addition, the neutron-proton mass difference leads to a slight breaking down of the isotopic-spin selection rules. However, it should be possible to evaluate, theoretically, the importance of such effects, and it is expected that careful investigations of the role of isotopic-spin selection rules in low-energy nuclear reactions will yield considerable information on the extent of the charge-independence of the strictly nuclear forces between nucleons.

Meson Theory

The Lévy potential, and its influence on the conference deliberations has been mentioned. What Lévy actually did was to compute the neutron-proton interaction for a symmetrical, pseudoscalar meson theory with pseudoscalar coupling.* He used a perturbation approximation, but tried to carry the calculation far enough to evaluate higher-order effects.

In the nonrelativistic approximations (which, according to Lévy, corresponds to nuclear kinetic energies of less than ~ 40 Mev), the interaction is represented by the following relatively simple potential (*1*): (1) A repulsive core, of radius of the order of the nucleon Compton wavelength, $\hbar/Mc$; (2) A "second-order" term, V_2, which contains the usual spin-dependent and tensor interaction terms, of range $\hbar/\mu c$ (μ is the π-meson mass); and (3) a fourth order term, V_4, which is spin-independent and of somewhat shorter range.

By an appropriate choice of two parameters, the radius of the repulsive core and the coupling constant $G^2/4\pi$, Lévy was able to obtain a reasonable fit to the low-energy properties of the neutron-proton system as well as to the data on n-p scattering up to 40 Mev.

Recent calculations, by Lévy and co-workers, on proton-proton scattering were reported at the conference. Using the same potential, they succeeded in fitting the experimental data at 18 and 32 Mev.

Another result of considerable significance was reported from MIT (work of S. M. Drell and K. Huang, reported by V. F. Weisskopf). This relates to the problem of "saturation" of nuclear forces—i.e., the fact that, despite a strongly attractive nuclear potential, nuclear matter maintains a constant, finite density (rather than collapsing). Starting from the Lévy potential between two nucleons, Drell and Huang computed the additional forces which result from the close proximity of 3, 4, or more nucleons. They found that forces among 3, 5, . . . bodies are repulsive, and that the 3-body force alone introduces enough repulsion to assure saturation with approximately the observed density of nuclear matter.

An estimate of the effect of the attractive 4-body force indicates that it does not spoil the saturation, and that when it and the rest of the series

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* A pseudoscalar meson is one of zero spin and negative parity, with respect to the proton; the π-meson is such a beast. Symmetrical means mesons of all signs treated equally, which assures charge independence of the forces. Pseudoscalar coupling means that the meson field is coupled to the nucleon field through the gradient of the latter.

are taken into account, there is reasonable expectation that the saturation properties will be maintained. If so, this will be a satisfactory solution to a long-standing dilemma, even though it would mean that two-body forces alone are insufficient to account for the known properties of nuclei.

FUNDAMENTAL π-MESON INTERACTIONS

The most fruitful field for the study of the nature of the π-meson interaction with nucleons is in the few available two-body reactions between π-mesons, nucleons, and photons. One of the most significant results of the 1951 conference was the presentation of strong evidence, from the scattering of π-mesons by nucleons, that the I-spin plays a dominant role in determining the nature of these interactions.

If we ascribe to the π-meson an intrinsic I-spin of $\tau = 1$ ($\tau_z = +1$, 0, -1 correspond, respectively, to π^+, π^0, and π^-) then the interaction of the π-meson with a nucleon ($\tau = \frac{1}{2}$) can take place in either of two possible states, $T = \frac{3}{2}$ or $T = \frac{1}{2}$, of the total I-spin. The old evidence, that the interaction is primarily in the state $T = \frac{3}{2}$, has been further confirmed and extended. It is encouraging, also, that the results of meson theory, insofar as the calculations have been successfully carried out, confirm these experimental indications.

Nucleon + Nucleon $\rightarrow d + \pi$

The reaction

$$p + p \rightleftarrows d + \pi^+$$

has been extensively investigated, in both directions, at Berkeley, Rochester, and Columbia. It was by application of the principle of detailed balancing to this reaction that the spin of the π-meson was shown to be zero. For energies such that the π-meson has a kinetic energy of ~ 55 Mev in the center-of-mass system, the angular distribution of this reaction is proportional to $0.2 + \cos^2\theta$.

Work was reported from Chicago (work by Hildebrand, reported by H. L. Anderson) on the complementary reaction

$$n + p \rightarrow d + \pi^0$$

Assuming charge-independence of the nucleon-meson interaction (which is equivalent to saying that the matrix element for the reaction depends only on the value of the total I-spin, which is unity in the case of the p-p reaction), the n-p reaction should have the same angular distribution as, and half the total cross section of, the p-p reaction. Hildebrand found, indeed, that the angular distribution in the n-p reaction is proportional to $0.2 + \cos^2\theta$. No measurements have as yet been made on the total cross section. This result is perhaps the strongest evidence, to date, for the charge-independence of the π-meson-nucleon interaction (which is, presumably, the origin of the nucleon-nucleon interaction).

The above-mentioned connections between the p-p and n-p reactions represent but one example of a set of general relationships between the various nucleon-nucleon, π-meson-producing interactions which can be derived from considerations of charge independence. These relationships have been explored by a number of investigators (reports by H. L. Anderson and L. Van Hove), and the results have recently been published (*2*).

Scattering of π-Mesons

Three reactions have been extensively investigated:

$$\pi^+ + p \rightarrow p + \pi^+$$
$$\pi^- + p \rightarrow n + \pi^0$$
$$\pi^- + p \rightarrow p + \pi^-$$

at Chicago ($E_\pi = 120$ and 135 Mev) and at Columbia and Rochester (lower π-meson energies). The fact that the total cross sections for these reactions are, roughly, in the ratio 9:2:1 was, even at the last conference, taken as a strong indication of the importance of the I-spin, since the above ratio of cross sections was predicted by Brueckner on the assumption that only states of $T = \frac{3}{2}$ are involved in the interaction.

In the past year, the Chicago group has carried out a series of investigations on the angular distributions of these reactions, on which a preliminary report has appeared in the literature (*3*). Improved measurements, mainly on the second of the above reactions, have since been carried out (reported by E. Fermi), and an analysis of the data shows that the reaction takes place predominantly in the state of ordinary angular momentum $J = \frac{3}{2}$ and I-spin $T = \frac{3}{2}$.

Two important points were brought out which still remain to be cleared up: (1) An alternative analysis of these data has been made by Yang which requires that the predominant reaction be in the state $J = \frac{1}{2}$, $T = \frac{3}{2}$. The latest data indicate that the Yang analysis provides a somewhat less good fit to the experiments, but it cannot be excluded. Further improvements and extensions of the experiments could remove the ambiguity. (2) The above-mentioned analysis indicate that the π-meson interacts with the proton mainly in the p-state, which is to be expected from the pseudoscalar (negative parity) nature of the π-meson. However, the analyses also indicate an appreciable interaction in the s-state. This interaction is considerably greater than predicted by any of the existing theories. Furthermore, its dependence on energy is not well understood, neither experimentally nor theoretically (*4*).

The theoretical understanding of meson scattering has also advanced considerably. Chew reported on calculations in which he considered higher-order corrections to a perturbation treatment in the nonrelativistic approximation. The result is to emphasize the interaction in the $J = \frac{3}{2}$, $T = \frac{3}{2}$ state, and to decrease the interaction in the other states. Indeed, the $\frac{3}{2}$, $\frac{3}{2}$ interaction, in the Chew calculation, takes on the aspect of a "resonance," which is also indicated in the experiments. A more exact calculation by Dyson, Bethe, and co-workers is tending to confirm Chew's results.

Photomeson Production

Important progress was reported in the investigation of two reactions

$$\gamma + p \rightarrow p + \pi^0$$
$$\gamma + p \rightarrow n + \pi^+$$

The results on π^0 production may be summarized as follows: Experiments at Cornell (*5*) and MIT (Y. Goldschmidt-Clermont, L. S. Osborne, and M. B. Scott), for γ-rays of energy up to 300 Mev, show that the cross section near threshold ($\sim$150 Mev) increases as the cube of the π-meson momentum in the center-of-mass system, and that the angular distribution is proportional to $a + b \sin^2\theta$, with $b/a \sim 1$–5.

The γ-ray energy range has been extended by the successful operation of a 500-Mev synchrotron at the California Institute of Technology, from which measurements were re-

ported (by R. F. Bacher) on the π^0 production cross section (at 90-deg to the beam) up to 450 Mev. The somewhat surprising result of these measurements is that the cross section appears to go through a relatively sharp resonance, with its peak at a γ-ray energy of $\sim$320 Mev, and falls to $\sim$25% of the peak cross section at 450 Mev.

Whether this represents a real resonance remains to be seen, but these results, coupled with the strong indications that the interaction appears to take place predominantly through an intermediate state of $J = 3/2$ and $T = 3/2$, point up the connection between meson scattering and photoproduction, and indicate a gratifying simplicity in the fundamental meson-nucleon interactions (*6*).

New measurements on the angular distribution in the second of the above reactions were reported from MIT (reported by L. S. Osborne) and Cornell (reported by R. R. Wilson). This distribution shows a decrease in the forward direction, with an angular distribution of the form $a - b\cos\theta$, with $b/a \sim 0.5$. Such a distribution indicates interference between mesons produced in an s- and a p-state (electric-dipole and magnetic-dipole γ-ray absorption, respectively).

The analysis of the photomeson reactions (discussed by H. A. Bethe and B. T. Feld) provides strong evidence for the connection between photoproduction and meson scattering; indeed, the same set of parameters seem to fit both sets of data. Again, however, there is some ambiguity in the interpretation, it being still possible to assume that the reaction takes place either in the state $J = 3/2$, $T = 3/2$ or in the state $J = 1/2$, $T = 3/2$. A comparison of the cross sections for the two reactions seems to eliminate the $T = 1/2$ state, but this is by no means conclusive as yet, owing to the difficulty of absolute cross section measurements with a bremsstrahlung γ-ray beam.

PROPERTIES OF UNSTABLE PARTICLES, OLD AND NEW

As is always the case at such conferences, a large fraction of the time was devoted to a discussion of the manifold data on the new unstable particles. In this field, accelerators have as yet little to contribute, and cosmic-ray investigations still provide the major source of new data. Instead of attempting to summarize separately the many excellent contributions, the following paragraphs represent this author's opinion as to the status of and connections between the observed unstable particles. These conclusions lean most heavily on reports from the Cal Tech group (reported by C. D. Anderson and R. B. Leighton), the MIT group (reported by C. Peyrou and B. Rossi), the Indiana group (reported by R. D. Thompson), and the Bristol group (reported by D. H. Perkins).*

The μ-Meson

This, the first meson to be discovered, is the major hard component of cosmic rays at sea level. Its mass is 210 m_e (electron masses) and its mean life is 2.1×10^{-6} sec. The decay scheme is $\mu^{\pm} \rightarrow e^{\pm} + 2\nu$ (ν = neutrino). Its spin is probably 1/2 and there is no indication of a neutral μ-meson.

The observations on μ-mesic X-rays from various elements, made at Columbia (reported by L. J. Rainwater), show indications of a fine structure, from which it should eventually be possible to obtain the magnetic moment. The Bristol group reports some indications of direct μ-meson production in nuclear disintegrations, but the extent of this production is not clear. Most μ-mesons come from π-meson decay.

The π-Meson

This is the meson primarily responsible for nuclear forces, at least at low energies. It is produced copiously by present-day accelerators and its properties have been discussed in a preceding section. There are three types, $\pi^{\pm}$ (mass $\approx$ 285 m_e) and π^0 (mass $\approx$ 275 m_e). The decay scheme of the charged π-mesons is $\pi^{\pm} \rightarrow \mu^{\pm} + \nu$ with a mean life of 2.8×10^{-8} sec. For the neutral meson, $\pi^0 \rightarrow 2\gamma$ and, alternatively, in about 1 out of 80 decays, $\pi^0 \rightarrow \gamma + e^+ + e^-$.

Observations on the alternative mode of decay, at Chicago (reported by M. Schein) and at Bristol, show that the electron pairs originate very close to the source of the π^0 and indicate a lifetime for the π^0 between 10^{-15} and 10^{-14} sec. A group at Rochester (reported by J. B. Platt) has observed π-mesic X-rays from carbon and oxygen.

The τ-Meson

There are now seven examples of τ-meson decays observed in nuclear emulsions, and several examples of decay in flight observed in cloud chambers. The decay scheme is probably

$$\tau^{\pm} \rightarrow \pi^+ + \pi^- + \pi^{\pm} + 75 \text{ Mev}$$

and the mass is about 975 m_e and the lifetime about 10^{-9} sec.

The V_1^0-Particle

Since the original report, by Rochester and Butler, of neutral and charged V-particles produced in cosmic-ray nuclear interactions, these particles have been widely studied. Of the various types reported, the V_1^0 now seems very well established, and has the decay scheme $V_1^0 \rightarrow p + \pi^- + 37$ Mev and a mean life of about 3×10^{-10} sec.

These are relatively abundant among the products of cosmic-ray nuclear interactions, but it is not yet certain that they can be produced alone (i.e., that they are not produced either in pairs or together with another type of unstable particle). In this regard, it is of great interest to see whether they can be produced by the available accelerators. On this question there is some rather inconclusive positive evidence from Chicago (reported by M. Schein) and Illinois, but the cross section, if not zero, is certainly very small. There is some evidence, not yet conclusive, that there may exist a charged counterpart to the V_1^0.

Other V-Particles

There appear to be at least two other types of neutral V-particles, as well as charged V-particles. Of the neutrals, the $V_2^0 \rightarrow \pi^+ + \pi^- + \sim$200 Mev (mass $\sim$ 950 m_e) seems reasonably well established, while $V_3^0 \rightarrow \pi +$ a heavier meson, and $V_4^0 \rightarrow 3$ mesons may also be indicated. These have lifetimes of the same order, or somewhat longer, than V_1^0, as have also the charged V-particles. I am inclined,

(*Continued on p. 60*)

* Because of the uncertainty as to its existence, the ζ-meson ($\zeta \rightarrow 2\pi + \leq 2$ Mev) will be omitted from this discussion. The arguments, pro and con, were reviewed by M. M. Shapiro and D. H. Perkins.

Wear Studies of Irradiated Carbide Cutting Tools

Isotope-tracer measurements, more accurate than microscopic examination, show a constant rate of tool wear. With proper choice of isotope and specific activity, G-M and autoradiographic techniques can be used under normal machining conditions

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NEUTRON IRRADIATION of carbide machining-tool tips provides a sensitive and accurate method of following cutting-tool wear.

In normal operation, tool wear proceeds more or less continuously. Microscopic examination, which necessitates interrupting the machining, cannot demonstrate this constant rate of wear. Consequently, it is necessary to machine until the cutting edge breaks down or until the wear has reached a given amount. A microscopic investigation, involving the data in Table 1, would require at least nine determinations at three cutting speeds because of the poor accuracy of the method.

Merchant, using radioisotopes, has shown (*1, 2*) that a linear relationship exists between tool wear and length of machining time. Our investigations show that the transfer of irradiated tool material to chips and distribution of the material on the work piece can be accurately measured by Geiger-Müller and autoradiographic methods. However, counting-rate and health-precaution considerations demand the proper isotope selection and optimum specific activity.

Irradiation of Tips

Two carbide tips—qualities 1 and 2 in Table 1—were irradiated in a neu-

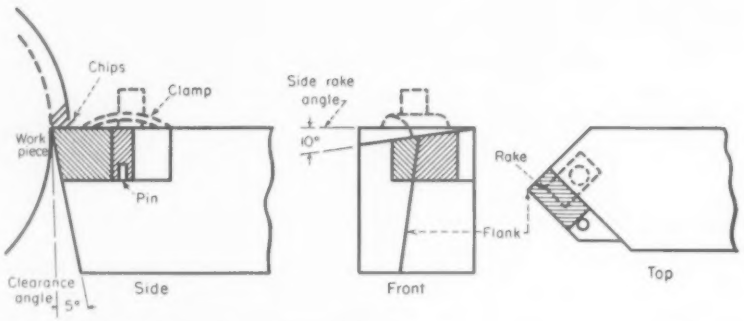


FIG. 1. Carbide-tip cutting tool characteristics

TABLE 1—Machining Specifications for Test Runs

Carbide tool composition

	Co (%)	TiC (%)	TaC (%)	WC (%)
Quality no. 1	7.2	3.5	2.5	86.8
Quality no. 2	9.3	4.7	—	86.0

Work-piece data

Billet dia. 200 mm, Brinell hardness 220 kg/mm²

C (%)	Mn (%)	Si (%)	P (%)	S (%)
0.58–0.60	0.80–1.10	0.20–0.24	0.04 (max.)	0.04 (max.)

Cutting data

Depth of cut = 2.0 mm
Feed = 0.5 mm/rev
Cutting speed = 100 m/min

Tool geometry

Nose radius = 1.0 mm
Clearance angle = 5°
Side rake = 10°
Side cutting edge angle = 45°
Nose angle = 90°
Machine: Skoda SUR Lathe 260 × 2,000 mm

* Division of Mechanical Technology.
† Division of Physical Chemistry.

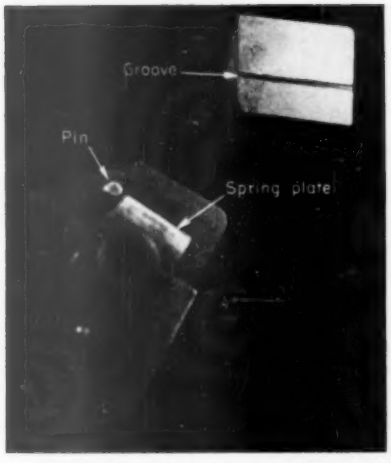


FIG. 2. Carbide tip (left) and tool shaft

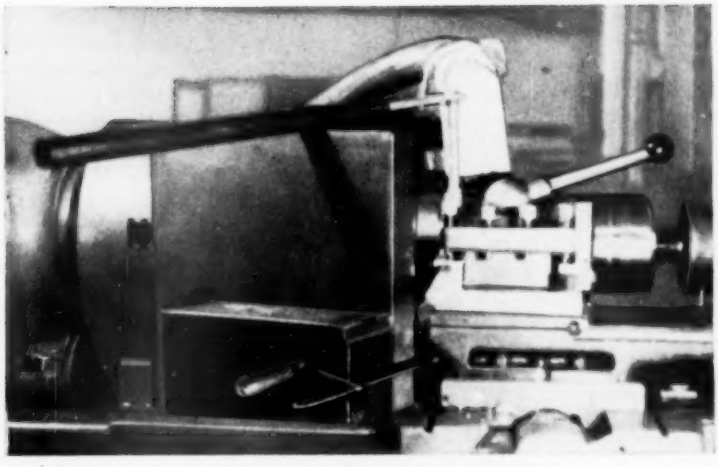


FIG. 3. Lathe with radiation shield and dust extractor in front

tron flux of 10^{12} n/cm²/sec for 1 hr. The isotopes Co^{60}, Ti^{51} (*3*), W^{185}, W^{187} and Ta^{182} were formed.

Choice of isotopes. The following points have to be considered:

1. The isotope must be formed in sufficient amount during irradiation.
2. The isotope must emit radiation suitable for detection.
3. The isotope must have a half-life long enough to allow for transportation from the pile and machining tests.
4. The half-life should, on the other hand, be short enough to minimize the need for handling precautions.
5. If possible, the isotope should be a pure beta emitter to avoid the health hazards involved in gamma emission.

Only the tungsten isotopes are formed in sufficient amount during a short irradiation (a few days) to require consideration. The nuclear data are given in Table 2 (*4*).

Both isotopes fulfill requirements 1–3. Requirement 5 is better satisfied by W^{185}. However, 4 greatly favors W^{187} because its 24.1-hr half-life necessitates precautions against health hazards for only one week or so. Furthermore, the shorter half-life and higher neutron-capture cross section of W^{187} require a shorter irradiation time. Thus, W^{187} is preferred for the present work.

Tungsten-187 is formed with a target-element cross section of 10.2 barns. Thus, only very short irradiations in a high flux of thermal neutrons are necessary for production of high activities.

Mechanical effects of irradiation. Prolonged bombardment in a high flux of fast neutrons may be supposed to cause certain changes in the crystal structure (*6*) and thus in the mechanical properties of carbide tips. However, if the irradiation takes place in the thermal shield of the pile, where the flux of fast neutrons is low, the risk of structural changes may be supposed to be small. In this case, mechanical properties are considered unchanged (*3*).

Desired Specific Activity

Preliminary experiments had shown that transfer of at least 5 mg of tip material could be expected from the rake (see Fig. 1) during a period of 20 min. This corresponds to a total of 2,000 meters of chips.

The G-M measurements were planned to be made with a 10% geometry (as calibrated with UX_2) and with a mosaic of small pieces of chip with a total length of 100 mm. Thus, the specific activity of the carbide tips necessary for a counting rate of 1,000 cpm is 20 mc/gm.

Now each tip weighed about 35 gm; thus, a total of 1.4 curies was necessary for two tips. This necessitates rather rigorous precautions as to health hazards, so an activity of only 10-mc/gm tip material was chosen, giving a counting rate of 500 cpm.

TABLE 2—Tungsten Isotope Data

Isotope	*Half-life*	*β-energy (Mev)*	*γ-energy (Mev)*
W-185	76 d	0.68, 0.48	—(*6*)
W-187	24.1 h	1.33 (30%), 0.63 (70%)	0.696, etc.

Machining Procedure

To reduce irradiation costs, the tips were irradiated before they were fastened to the shafts. Complications would be expected if the activated tips were attached to the shaft with the usual soldering and polishing method. Therefore a clamping method was used.

Figure 2 shows one of the cemented carbide tips ground to shape and ready for mounting on the tool shaft. The edge of the spring plate is pressed against the groove cut across the top surface of the tip. The pin holds the tip in position during machining.

Turning is carried out in the normal manner except that the tips are handled by remote control. Operators are protected by a shield and a fan to remove radioactive dust (Fig. 3). A filter in the fan, checked after the work is finished, exhibits no contamination.

The feed is engaged for 30 sec. The tool is then unfastened and mounted in position for photographing the top surface of the tip. The last chips to be formed during each 30-sec operation are collected and measured with the G-M counter. The tip of quality no. 1 was used for a total of 35 runs of 30 sec each, and no. 2, for 43 runs.

Preparation of Chips

The turning chips, almost flat to start with, become more and more

curved towards the end of the cutting-tool life.

The flat chips are cut into pieces of 2-cm length. Five pieces are placed side by side to form a square on a Perspex disk. This is centered under an end-window G-M tube

The curved chips are broken into small pieces of a few millimeters length. These pieces are built up into a mosaic of approximately the same area as the groups of flat chips.

The exact width, total length, and thickness of each group of chips is measured. The activity of one of the groups was followed for a few days, giving a half-life of 24 hr.

Activity Measurement

To calculate the absolute amount of material transferred to the chips, one of two methods can be used:

1. The specific activity of the carbide tips can be calculated from irradiation and nuclear data, if the counter efficiency is known.

2. A weighed piece of the same material as the tip, used as a reference source, is irradiated together with the tip. The piece is dissolved in a suitable chemical agent. A known part of the solution is evaporated, and the activity is measured under identical geometrical arrangements as for the measurements of the chips. Dividing all activity figures for the turnings with this figure gives directly the corresponding amount of radioactive material.

In the present work, the second method is used. The first method gives a check of the results.

Reference sources. As the activity of the small reference pieces is too high to be measured without dilution, these are dissolved in molten sodium nitrite, the tungstate dissolved in water, and 1/1,000 of the solution evaporated on an iron disk with the same area and bottom thickness as the turnings, thus making backscattering corrections unnecessary.

The activity of the reference sources is measured under the same geometrical arrangements as for the chips. These operations are performed two days after the other work. Because of this, the reference-source activities are followed for a long period to permit an exact extrapolation.

The curves show that a small amount of a long-lived activity was present in the sources. After complete decay of the W^{187}, this remaining activity is determined and subtracted from the total source activity.

A linear semi-logarithmic relation between activity and time results. The half-life values for W^{187} calculated from these curves are 23.9 and 24.2 hr, respectively. These are very close to the accepted figure of 24.1 hr (*4*).

Calculations and Results

For each group of turnings, a total of about 3,000 counts was made, giving a statistical error of 2%. All radioactivity figures are corrected for the deadtime of the counting equipment, for the background, and for the half-life of W^{187} (24.1 hr).

A separate experiment was made to find the relation between area and counting rate (to correct for the differences in area of the chips). This experiment showed that, within the range of areas used (230–350 mm^2), this relation is linear. No corrections for the backscattering of the beta particles are needed since the thickness of the chips gave saturation backscattering [backscattering factor = 1.45 (*3*)].

The beginning of each run is fixed as "zero time." All radioactivity figures are corrected back to that time.

The corrected counting-rate figures for the chips are divided by the counting rate of the corresponding reference source, giving the weight of the carbide-tip material transferred during a certain period. The length of this period can be calculated from the cutting data (including the cutting ratio, i.e., the ratio chip thickness before:after removal), and thus the material transferred in gm/min can be determined.

Figure 4 shows that the material transferred per minute from the tip of quality no. 2 is almost constant. Quality no. 1 shows a large transfer during an initial period of 3 min, followed by an almost constant wear.

The total amount transferred, found by integrating the curves of Fig. 4, is given in Fig. 5. As may be expected, the curve for quality no. 1 is a straight line; for quality no. 2, the relation is linear after the initial period.

All the above figures of counting rate correspond to material transferred from the rake side of the carbide tip. Only for one group of turnings was the transfer from the flank also measured. For this group of chips, the rake-to-flank ratio is 3.5.

The chips corresponding to 14.5 min turning with quality no. 2 gave an extraordinarily high counting rate (9,000 cpm, the ordinary being 400 cpm). This was due to one piece. A small piece of the carbide tip had broken off and cut a groove in the chip,

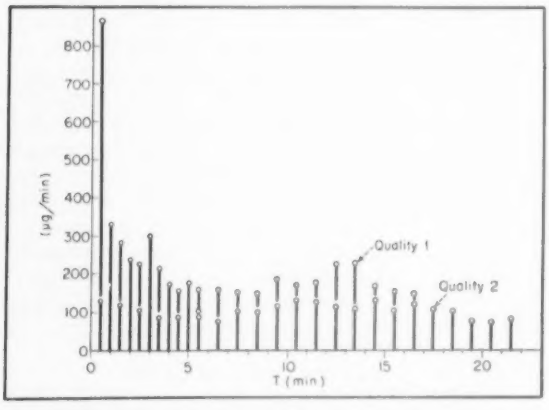


FIG. 4. Rate of material transfer from rake side to turnings

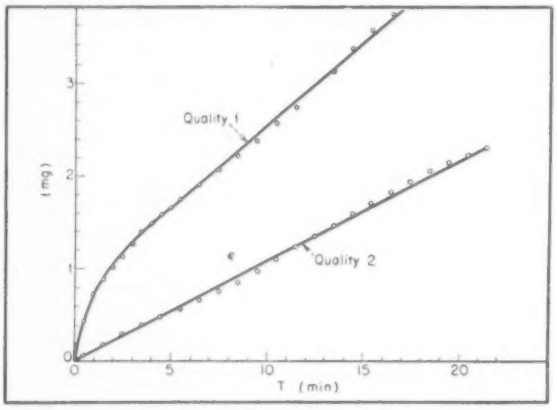
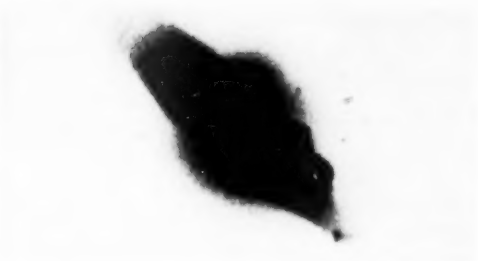


FIG. 5. Total wear of rake side as function of time



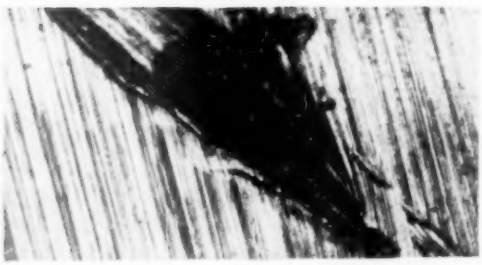


FIG. 6. Chip having abnormally high activity because of broken off piece of carbide tip. (Top) Autoradiograph (7). (Bottom) Micrograph

FIG. 7. Autoradiograph of work piece after turning (film: Ilford C)

FIG. 8. Autoradiograph of chip formed after 30-sec turning (film: Ilfex)

where it finally stuck. The size of this piece, calculated from the activity, was 15 μg. An autoradiograph [Kodak autoradiographic plate (7)] and a micrograph are shown in Fig. 6.

Counting efficiency. From irradiation and nuclear data, the specific activity of the tips immediately after the irradiation is 25 mc/gm tungsten (corresponding to 10 mc/gm during the experiments). Comparison of this figure with the activity of the reference sources, corrected for the difference in time, gives a total efficiency for the counting equipment of 12%, which within the limits of error is equal to the 10.5% found when using a UX_2 standard source. Of course, since the neutron flux is not known exactly, this check is only approximate. The error in the flux is probably $< 20\%$ (3).

Autoradiographs. Because of the relatively low activity, autoradiographs of the work piece and turnings were not distinct. A work-piece autoradiograph is shown in Fig. 7, and another (one of the turnings), in Fig. 8.

From Fig. 7, it is seen that the material transfer to the work piece is distributed partly evenly (the faint lines) and partly discontinuously (the black spots). This region of spots and marked lines corresponds to start or finish of a run. This is verified by the fact that the axial distance between two such regions (one of which is shown) is equal to the length of the transfer of the tool during a 30-sec run.

The autoradiograph of the turning, Fig. 8, is very faint but shows no marked discontinuities.

Discussion

This investigation confirms that, with these materials and cutting data, there exists a linear relationship between the rake transfer and the turning time. If this relationship is obtained with other materials and data, it will be possible to make a comparison between different qualities of carbide tips without machining until the cutting edge of the tip breaks down.

A material-transfer-versus-time curve could be constructed after only a few runs of 30 sec each. The slope of this graph gives an idea of the cutting-tool life. However, if a group of curves of the second order, which do not intersect, is obtained, a comparison can be made by measuring the slopes.

According to Merchant, the accuracy of the radioactive method is better than that of conventional methods, and, moreover, the cost of making a test is relatively low. Merchant has also shown that, when using cutting fluid, more than 95% of the activity is attached to the turnings.

Merchant made the radioactivity measurements on all turnings formed during a very short period by means of a gamma-sensitive G-M tube, thus giving the sum of the activities on both sides of the turnings. The present method, however, gives the amount of material transferred to one side only, thus permitting separate investigation of each side.

* * *

The authors wish to express their thanks to Professors R. Woxén, head of the Div. of Mechanical Technology, O. Lamm, head of the Div. of Physical Chemistry, and O. Andersson, acting Professor at the Div. of Mechanical Technology, for their kind interest in this work and for placing laboratory facilities at our disposal, and Messrs. T. Westermark and G. Aniansson for preliminary calculations and valuable discussions. Thanks are also due to Mr. C. Lindberg for skillful technical assistance.

The nucleonic equipment used in this work was placed at our disposal by the Swedish Atomic Committee.

The irradiations were made by AERE, Harwell, England, and the valuable help of Mr. J. L. Putman is also gratefully acknowledged.

Health precautions were supervised by Dr. S. Benner of the Radiophysical Department, Karolinska Institutet, Stockholm.

Further research on this method will be carried out at the Div. of Mechanical Technology, this being made possible by the State Council of Technical Research who have kindly placed funds at our disposal for this investigation.

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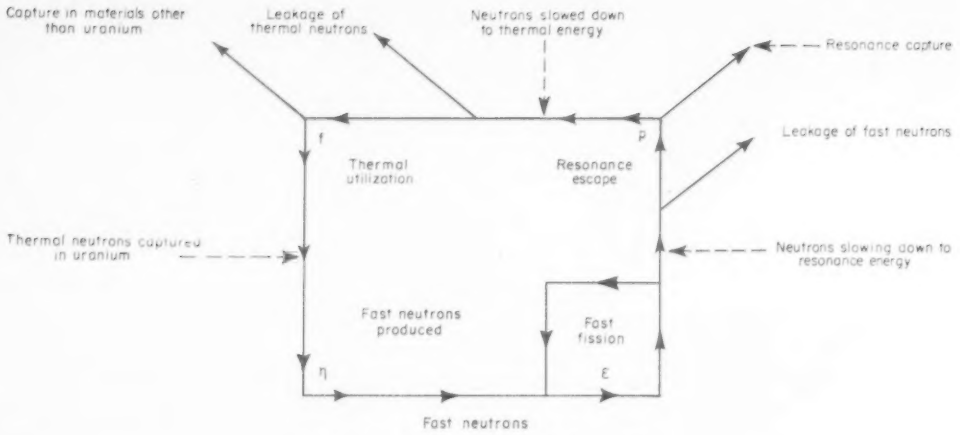

FIG. 1. Cycle of neutrons in a reactor

Uranium-Graphite Lattices

Extensive calculations have been made for possible piles of natural uranium rods arranged as a lattice in graphite. Details of the methods and the results of the calculations are given here for seven important quantities, including the critical amount of uranium, the reproduction constant, and the migration length

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URANIUM RODS arranged in the form of a lattice surrounded by graphite constitute one basic form of reactor. This article describes calculations and results for such natural uranium piles for variations in the arrangement of the lattice.

The most important quantities determined by the calculations are: the quantity, U, of uranium required for the pile to react steadily; the reproduction constant, k; the square of the migration length, M^2; and the "Laplacian," $\kappa^2 = (k-1)/M^2$. These quantities are described in detail by Glasstone and Edlund (*1*).

The following characteristics are common to all the piles studied:

1. The reacting core is a circular cylinder with equal height and diameter; this differs insignificantly from the ratio of height to diameter which permits the minimum cylindrical pile for a given lattice.

2. The reacting core is completely surrounded by a graphite reflector.

3. The uranium is in the form of parallel rods arranged in a square or regular hexagonal lattice.

The following are the characteristics which have been varied:

1. The radius, a, of the uranium rods.

2. The "pitch" between rods; it is convenient to measure this by a length, b, such that the cross sectional area per rod is πb^2. The dependence of U, k, etc., on b is then, to the accuracy of the calculations, independent

of whether the lattice is square or hexagonal.

3. The width, $c - a$, of an air gap surrounding each rod.

4. The thickness, t, of aluminum sheath surrounding each rod.

Notation

The reproduction factor, k, of the lattice is defined as the product of four factors η, ϵ, f, and p, whose meaning and definition are readily understood by reference to the schematic neutron cycle shown in Fig. 1. One of these factors appears near each corner of the square, and denotes the ratio of the number of neutrons emerging from the corner to the number of neutrons approaching the corner.

The capture of one thermal neutron in uranium gives rise to η primary fission neutrons.

Proceeding counterclockwise around the cycle, a fission neutron, before it is slowed down, may cause a fission in uranium and so give rise to more fission neutrons, which in their turn may cause further fissions, and so on; for each primary fission neutron, ϵ neutrons which eventually get slowed down are produced.

Continuing around the cycle, an unspecified fraction of neutrons leaks out of the lattice before reaching resonance energy; of those that remain, a fraction p escapes resonance capture in U^{238}.

A further unspecified fraction leaks out before being captured in the lattice; of those that remain, a fraction f, called the thermal utilization factor, is captured in uranium and the cycle starts afresh.

The condition for a steadily reacting pile, if there were no leakage of neutrons to the outside, would be $k = 1$. Since, however, there always is such leakage, the actual condition is that k should have a value depending on the size of the pile. This required "excess k" increases as the size of the pile decreases, and tends to zero for an infinitely large pile.

Characteristic lengths. The several characteristic lengths of the lattice are defined as follows.

The slowing down length, L_s, is such that the mean square of the distance traveled by a neutron after creation by fission, and until its kinetic energy is reduced to the thermal equilibrium value, is $6L_s^2$.

The diffusion length, L, is such that the mean square of the distance traveled by a neutron with thermal energy before capture is $6L^2$.

The migration length, M, is such that the mean square of the distance traveled by a neutron between its creation by fission and its capture is $6M^2$, so that $M^2 = L_s^2 + L^2$.

The critical linear dimensions of a pile of given shape (in particular, a circular cylinder of height equal to diameter) are closely related to, and determined by, a characteristic length called the multiplication length, which is denoted by κ^{-1}. Its inverse square, κ^2, is commonly called the Laplacian. The approximate formula that determines κ^2 is $\kappa^2 = (k - 1)/M^2$.

The critical radius for a pile of given lattice without a reflector, is denoted by R_0, and the critical radius for a pile of the same lattice with a graphite reflector, by R_r. The critical quantity of uranium is denoted by U.

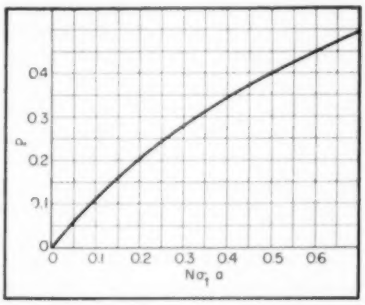

FIG. 2. Relation between P and $N\sigma_t a$

General Procedure

The various steps of a complete calculation are briefly as follows. The fast fission factor, ϵ, the thermal utilization factor, f, and the resonance escape factor, p, are calculated, and the product of η, ϵ, p, and f gives the value of k.

The slowing down length, L_s, and the diffusion length are calculated. These are combined with $k - 1$ to give κ^2 and R_0, the radius of a critical pile without a reflector. This value of the radius is then corrected for the effect of a reflector.

Finally, from the geometry of the lattice and the radius of the reacting core, the calculation of U, the quantity of uranium, is straightforward.

Primary Fission Neutrons

For lattice calculations, it is the usual practice to compute values of all the other relevant quantities and then derive a value of η from exponential experiments on particular lattices. The value used in these calculations is $\eta = 1.308$.

Fast Fission Factor

The fast fission factor, ϵ (2), is the ratio of the total number of neutrons produced by fission to the number of neutrons produced by fission by thermal neutrons.

We use for ϵ a simplified version of Eq. 9.82.1 of Glasstone and Edlund, namely

$$\epsilon - 1 = \frac{(\eta - 1)(\sigma_a/\sigma_t)P}{1 - \frac{\eta\sigma_a + \sigma_e}{\sigma_t}P} \qquad (1)$$

where σ_a is the absorption cross section for fast neutrons, that is, the sum of the fission and capture cross sections; σ_e is the elastic cross section for fast neutrons; σ_i is the inelastic cross section for fast neutrons; σ_t is the total cross section for fast neutrons; and $\sigma_t = \sigma_a + \sigma_e + \sigma_i$. The quantity η is the number of neutrons arising from the absorption of a fast neutron, and $1 - P$ is the probability that a neutron inside a uranium rod will escape before suffering any further collisions.

The quantity P is the function of $N_0\sigma_t a$ shown in Fig. 2, where N_0 is the number of uranium atoms per unit volume, and a is the radius of a rod.

The value assumed for σ_t is 4.3×10^{-24} cm^2, and, for uranium of density 18.9 gm/cm^3, $N_0 = 0.04784 \times 10^{24}$, so that $N_0\sigma_t = 0.205$ cm^{-1}.

Numerical values were assumed for the coefficients of P in the numerator and denominator of Eq. 1, so that this formula becomes

$$\epsilon - 1 = \frac{0.0948\,P}{1 - 0.521\,P} \qquad (2)$$

These numerical coefficients are such that when $a = 1.7$ cm, the calculated value of $\epsilon - 1$ is 0.035, which is in agreement with experimental data from Argonne. If one assumes $\sigma_t = 4.3 \times 10^{-24}$ cm^2, and $\sigma_e = 1.5 \times 10^{-24}$ cm^2, for which the experimental information is relatively good, then our formula corresponds to the assumptions $\sigma_a = 0.33 \times 10^{-24}$ cm^2, $\sigma_i = 2.47 \times 10^{-24}$ cm^2, and $\eta = 2.25$, none of which is particularly unreasonable.

Equation 2 should be regarded as a semi-empirical, but probably adequate, formula for interpolation and extrapolation from accepted values of $\epsilon - 1$ for $a = 0$ and $a = 1.7$ cm.

The values of P for various values of

a are taken from Fig. 2, and the values for $\epsilon - 1$ from Eq. 2.

Thermal Utilization Factor

The thermal utilization factor, f, is the ratio of the number of thermal neutrons captured in uranium to the total number of thermal neutrons captured in lattice. Alternatively, the competitive absorption, $(1/f) - 1$, is the ratio of the number of thermal neutrons captured by materials other than uranium to the number of thermal neutrons captured by uranium.

If the core were a homogeneous mixture of uranium, graphite, and aluminum, we should have the simple relation

$$\frac{1}{f} - 1 = \frac{N_1\sigma_1}{N_0\sigma_0} + \frac{N_2\sigma_2}{N_0\sigma_0} \qquad (3)$$

where N is the number of atoms per unit volume, σ is the atomic absorption cross section, and the subscripts 0, 1, 2 refer to uranium, graphite, and aluminum, respectively.

We are, however, not concerned with a homogeneous core but with a core in which the uranium, graphite, and aluminum are separate and occupy volumes which we denote by V_0, V_1, and V_2, respectively.

If we denote the radius of a uranium rod by a, the thickness of the aluminum sheath by t, the width of the air gap by $c - a - t$, and the radius of a cell by b, then

$$V_0/V_1/V_2 = a^2/(b^2 - c^2)/(2at + t^2) \qquad (4)$$

or, with sufficient accuracy for thin sheaths,

$$V_0/V_1/V_2 = a^2/(b^2 - c^2)/2at \qquad (5)$$

If the neutron density were uniform throughout this pile, which it is not, we should have the simple relation

$$\frac{1}{f} - 1 = \frac{N_1\sigma_1V_1}{N_0\sigma_0V_0} + \frac{N_2\sigma_2V_2}{N_0\sigma_0V_0} = \frac{N_1\sigma_1(b^2 - c^2)}{N_0\sigma_0a^2} + \frac{N_2\sigma_2 2t}{N_0\sigma_0a} \qquad (6)$$

Equation 6 gives an approximate value of f sufficient for some qualitative considerations, but it is inadequate for our present purpose, and has to be corrected to take account of nonuniformity in the neutron density.

For the required modification, we begin by considering the simpler system consisting of uranium and graphite without aluminum. Instead of Eq. 6, we have for the competitive absorption of the graphite

$$\frac{1}{f} - 1 = \frac{N_1\sigma_1V_1\rho_1}{N_0\sigma_0V_0\rho_0} \qquad (7)$$

where ρ_0 denotes the mean neutron density in the uranium, and ρ_1 the mean neutron density in the graphite. The neutron distribution is shown schematically in Fig. 3. In view of the shape of this distribution, it is convenient to regard the competitive absorption of the graphite as the sum of two terms written as

$$1/f - 1 = R + S \qquad (8)$$

The term R is called the "relative absorption term" and denotes, per thermal neutron captured in uranium, the number of thermal neutrons which would be captured in the graphite if the neutron density in the graphite were uniformly equal to the density in the air gap. The term S is called the "excess absorption term" and denotes, per thermal neutron absorbed in uranium, the excess number of thermal neutrons captured in graphite due to the excess density of neutrons in the graphite over the density in the air gap.

The formulas for R and S for the case of no air gap are derived in Glasstone and Edlund (3) according to classical diffusion theory. Their extension to the case of a gap, neglecting any absorption by the air in the gap, is straightforward. In this treatment, it is assumed that the net flux of thermal neutrons across the boundary of a cell is zero. This assumption is strictly correct only in the limit of an infinitely large pile with $k = 1$, but is considered an adequate approximation for a finite pile. The resulting formulas are

$$R = \frac{N_1\sigma_1V_1}{N_0\sigma_0V_0}G_0(\kappa_0a) \qquad (9)$$

$$S = X_1(\kappa_1c, \kappa_1b) \qquad (10)$$

where κ_0 and κ_1 denote the inverse diffusion lengths in uranium and graphite, respectively, and G_0 and X_1 are defined, as follows, in terms of the Bessel functions of imaginary argument

$$G_0(x) = \frac{xI_0(x)}{2I_1(x)} = 1 + \frac{1}{2}\left(\frac{x}{2}\right)^2 - \frac{1}{12}\left(\frac{x}{2}\right)^4 + \frac{1}{48}\left(\frac{x}{2}\right)^6 - \frac{1}{180}\left(\frac{x}{2}\right)^8 + \cdots \qquad (11)$$

$$X_1(z,y) = \frac{y^2 - z^2}{2z} \times \frac{I_1(y)K_0(z) + |K_1(y)|I_0(z)}{I_1(y)|K_1(z)| - |K_1(y)|I_1(z)} - 1 \qquad (12)$$

The value $G_0(x)$ is plotted against x in Fig. 4 for the range of values required for graphite lattices.

Contours of $X_1(\kappa_1c, \kappa_1b)$ as functions of κ_1c and κ_1b are given in Fig. 5 for the domain of values required in practice for graphite lattices.

If $\kappa_1b < 0.4$, the approximate formula

$$X_1(\kappa_1c,\kappa_1b) = \frac{\kappa_1^2b^2}{2} \times \left[\frac{b^2}{b^2 - c^2}\ln\frac{b}{c} - \frac{3}{4} + \frac{c^2}{4b^2}\right] \qquad (13)$$

is accurate to within 0.001.

We now proceed to describe the modification of our formulas if there is a thin aluminum sheath of thickness t around the uranium. Instead of Fig. 3 we now have Fig. 6. Instead of Eq. 8, it is now convenient to write, formally,

$$1/f - 1 = R_1 + B_1 + S_1 + R_2 + S_2 \qquad (14)$$

The several terms of the competitive absorption are shown schematically in Fig. 6. The term R_1 is called the "graphite relative absorption term" and denotes, per thermal neutron captured in uranium, the number of thermal neutrons which would be captured in the graphite if the neutron density in the graphite were uniformly equal to the density at the uranium-aluminum interface. The term S_1 is called the "graphite excess absorption term" and denotes, per thermal neutron captured in uranium, the excess number of thermal neutrons captured in graphite due to the excess density of

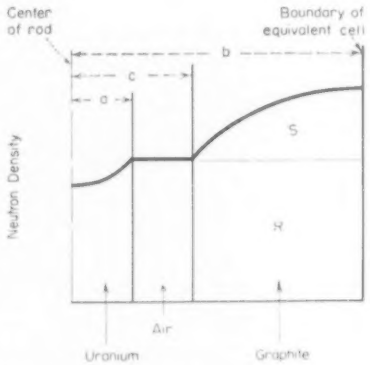

FIG. 3. Neutron distribution in a uranium-graphite lattice

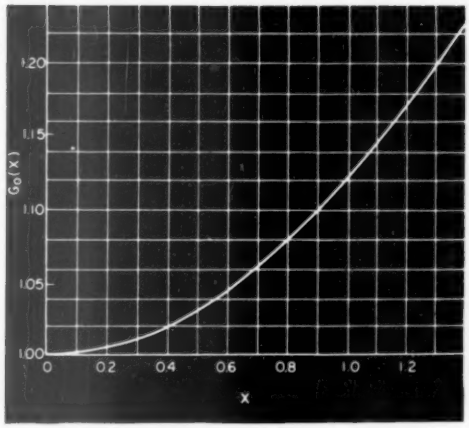

FIG. 4. The function $G_0(x)$

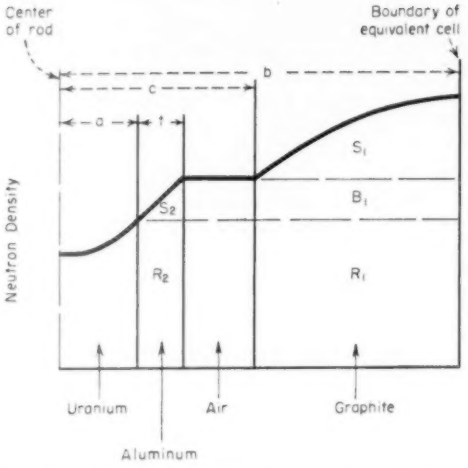

FIG. 6. Neutron distribution in a uranium-graphite lattice for aluminum-clad rods

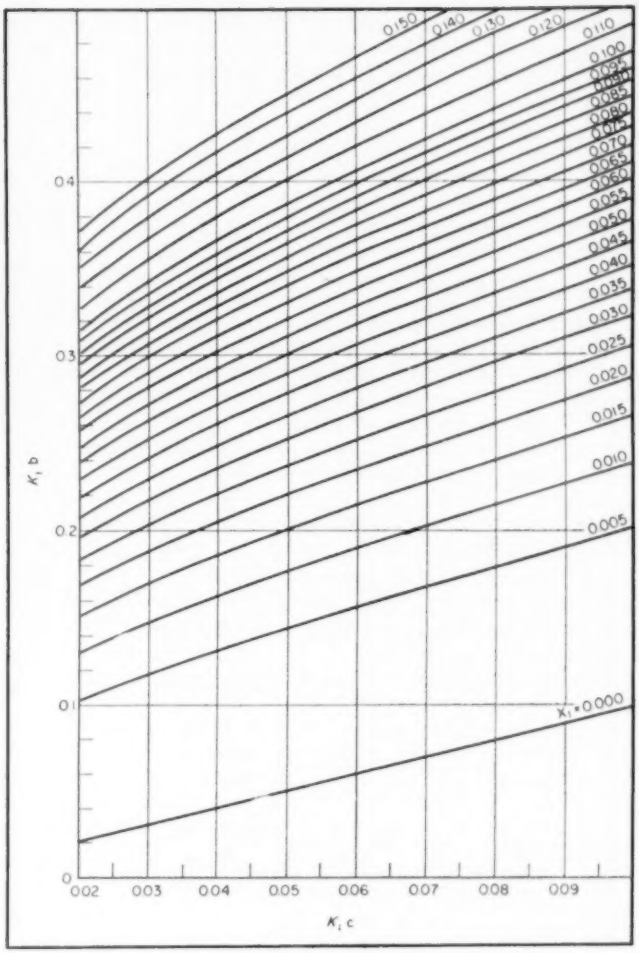

FIG. 5. Contours of the function $X_1(\kappa_1 c, \kappa_1 b)$

neutrons in the graphite over the density at the graphite-air interface.

The term R_2 is called the "aluminum relative absorption term" and denotes, per thermal neutron captured in uranium, the number of thermal neutrons which would be captured in the aluminum if the neutron density in the aluminum were uniformly equal to the density at the uranium-aluminum interface. The term B_1 is called the "aluminum-graphite blocking term" and denotes, per thermal neutron captured by uranium, the number of thermal neutrons captured in the graphite due to an increase in neutron density from that at the uranium-aluminum interface to that at the graphite-air interface. Finally, S_2 is called the "aluminum self-blocking term" and denotes, per thermal neutron captured in uranium, the excess number of thermal neutrons captured in aluminum due to the excess density of neutrons in the aluminum over the density at the uranium-aluminum interface.

From classical diffusion theory, neglecting certain terms proportional to t^2 and higher powers of t, the following formulas are obtained

$$R_1 = \frac{N_1\sigma_1 V_1}{N_0\sigma_0 V_0} G_0(\kappa_0 a) \qquad (15)$$

$$R_2 = \frac{N_2\sigma_2 V_2}{N_0\sigma_0 V_0} G_0(\kappa_0 a) \qquad (16)$$

$$S_1 = (1 + R_2) X_1(\kappa_1 c, \kappa_1 b) \qquad (17)$$

$$B_1 = \frac{l_{s1}}{l_{s2}} (\kappa_1 a)^2 \frac{V_1}{V_0} \frac{t}{2a} \qquad (18)$$

$$S_2 = \frac{1}{2} (\kappa_2 a)^2 \frac{V_2}{V_0} \frac{t}{2a} \qquad (19)$$

where G_0 and X_1 are defined by Eqs. 11 and 12, respectively; and l_{s1} and l_{s2} are the scattering mean free paths in graphite and aluminum, respectively.

In view of Eq. 17, one may rewrite Eq. 14 in the form

$$\frac{1}{f} - 1 = R_1 + X_1 + [R_2 + R_2 X_1 + B_1 + S_2] \qquad (20)$$

where the terms in the brackets may be regarded as due to the aluminum.

The following values of the constants have been used in our calculations: $\kappa_0 = 0.770$ cm^{-1}, $\kappa_1 = 0.0200$ cm^{-1}, $N_0 = 4.784 \times 10^{22}$ atoms/cm^3, which corresponds to a uranium density of 18.9 gm/cm^3, $N_1 = 8.030 \times 10^{22}$ atoms/cm^3, which corresponds to a graphite density of 1.60 gm/cm^3, $N_1\sigma_1/N_0\sigma_0 = 1.31 \times 10^{-3}$, $N_2\sigma_2/N_0\sigma_0 = 0.04$, and $l_{s1}/l_{s2} = 0.2$.

To illustrate the relative importance of the several terms in the competitive

absorption, the following values are quoted from a sample calculation done for $a = 1.0$ cm, $c - a = 1.0$ cm, $t = 0.115$ cm, and $b = 9.0$ cm. The results obtained were $R_1 = 0.1082$, $X_1 = 0.0137$, $R_2 = 0.0099$, $R_2X_1 = 0.0001$, $B_1 = 0.0004$, S_2 negligible, $1/f - 1 = 0.1323$, and $f = 0.8834$. The rough result obtained by using Eq. 6 is $1/f - 1 = 0.088$ and $f = 0.919$.

Resonance Capture

The resonance escape factor, p, is defined as the probability that a neutron escapes resonance capture in uranium.

In all our calculations of p, any effect of aluminum has been consistently neglected. This seems reasonable, since on the one hand the slowing down effect of the aluminum is negligible compared with that of the graphite, and on the other hand, so far as is known, there is no appreciable capture by aluminum of neutrons that have energies above thermal.

In a homogeneous mixture of uranium and graphite, a sufficiently accurate expression for p would be

$$p = \exp\left[-\int \frac{N_0\sigma_{c0}(E)dE/E}{[N_1\sigma_{s1} + N_0\sigma_{c0}(E)]\xi} \right] = \exp\left[-\frac{N_0}{N_1\sigma_{s1}\xi} \int \frac{\sigma_{c0}(E)dE/E}{1 + \frac{N_0\sigma_{c0}(E)}{N_1\sigma_{s1}}} \right] \quad (21)$$

where, as previously, N is the number of atoms per unit volume, and the subscripts 0 and 1 refer to uranium and graphite respectively. Furthermore, $\sigma_{c0}(E)$ is the atomic capture cross section of uranium for neutrons of energy E, and σ_{s1} is the atomic scattering cross section of graphite, assumed independent of neutron energy in the range of integration; ξ is the mean logarithm of the ratio of the energy of a neutron before a collision to its energy after a collision with a carbon atom. The range of integration extends over all the resonance bands. We now define the quantity T by

$$p = e^{-1/T} \quad (22)$$

We then have

$$T = \frac{N_1\sigma_{s1}\xi}{N_0 \int \frac{\sigma_{c0}(E)dE/E}{1 + N_0\sigma_{c0}(E)/N_1\sigma_{s1}}} \quad (23)$$

The problem of calculating p is thus transformed to that of evaluating the integral in the denominator of the expression for T.

Turning now to a heterogeneous system consisting of a lattice of uranium in graphite, we continue to define a quantity T by Eq. 22. The theory as developed up to now does not lead to any precise and compact formula for T, but it is customary to write

$$T = \frac{N_1V_1\rho_1}{N_0V_0\rho_0} \frac{\sigma_{s1}\xi}{(\int\sigma_0 dE/E)_{eff}} \quad (24)$$

where, as usual, V_0 and V_1 are the volumes of uranium and graphite, respectively, and ρ_0 and ρ_1 are the average densities of resonance neutrons in the uranium and graphite, respectively. The expression $(\int\sigma_0 dE/E)_{eff}$ is a rather ill-defined quantity analogous to the integral in the denominator of Eq. 23. It is assumed to depend on the size and shape of the uranium rods but to be independent of their spacing and of the properties of the moderator.

The problem of calculating p is thus transformed to the following two problems: (a) estimation of the ill-defined integral in Eq. 24, and (b) estimation of the ratio ρ_0/ρ_1. We shall consider these in turn.

With regard to the first of these problems, we adopt the procedure described by Glasstone and Edlund (*4*), and use the empirical formula (valid for radii not less than 0.3 cm.)

$$(\int\sigma_0 dE/E)_{eff} = 9.25 \times 10^{-24}\ \text{cm}^2 \times \left[1 + 2.67\,\frac{S/\text{cm}^2}{M/\text{gm}}\right] \quad (25)$$

where M is the mass and S the surface area of a uranium rod. The first term on the right corresponds to the absorption of neutrons distributed more or less uniformly throughout the uranium rod, and the second term corresponds approximately to absorption of neutrons in a surface layer. The latter can be identified with those neutrons that enter the uranium with an energy very close to one of the resonance energies and are therefore captured almost immediately on entering. The more uniform capture can be associated with neutrons that enter the uranium with an energy less near to one of the resonance energies and can travel some considerable distance before being captured.

We have followed Wigner and Weinberg in introducing corrections for the deviation from unity of the factor ρ_0/ρ_1. We have done so because we have followed Wigner's school in our calculations of other quantities; we have used their assumed values for the various constants, and the final estimates should be, as far as possible, comparable to those made by Wigner and his colleagues (*4*).

Turning now to the second of the problems, we consider a specified energy range which effectively includes all the resonance levels of uranium, and refer to all neutrons having energies in this range as resonance neutrons. These resonance neutrons are created by the slowing down of fast neutrons in the graphite. They are destroyed either by capture in uranium or by slowing down to an energy below the lowest energy of resonance neutrons.

If one writes down the equations for the distribution of resonance neutrons, one finds that these have a striking resemblance to those for thermal neutrons, provided one introduces fictitious inverse diffusion lengths, κ'_0 and κ'_1, for the uranium and graphite respectively (*5*). Strictly, the value of κ'_0 should, like the integral in Eq. 24, depend on the radius, a, of a rod, but it is entirely adequate to ignore this dependence on a and regard κ'_0 as a constant characteristic of uranium.

The final result of the Wigner-Weinberg correction is to change Eq. 24 into

$$T = \frac{N_1V_1}{N_0V_0} \frac{\sigma_{s1}\xi}{(\int\sigma_0 dE/E)_{eff}} G_0(\kappa'_0 a) + X_1(\kappa'_1 c, \kappa'_1 b) \quad (26)$$

where $G_0(x)$ and $X_1(z,y)$ are precisely the same functions defined by Eqs. 11 and 12 for the calculation of thermal utilization.

Contours of $X_1(\kappa'_1 c, \kappa'_1 b)$ as functions of $\kappa'_1 c$ and $\kappa'_1 b$ are given in Fig. 7 for the domain of values required in practice for graphite lattices. The values of $G_0(x)$ are shown in Fig. 4.

Since in all our calculations we have assumed that the uranium is in the form of long cylindrical rods of radius a and density 18.9 gm/cm³, we can rewrite Eq. 25 as

$$(\int\sigma_0 dE/E)_{eff} = 9.25 \times 10^{-24}\ \text{cm}^2 \left(1 + \frac{2.67 \times 2}{18.9\ a/\text{cm}}\right) = 9.25 \times 10^{-24}\ \text{cm}^2 \left(1 + \frac{0.282}{a/\text{cm}}\right) \quad (a > 0.3\ \text{cm}) \quad (27)$$

For graphite, ξ is given by (*6*)

$$\xi = 1 - \frac{11^2}{2 \times 12} \log\frac{13}{11} = 0.1578 \quad (28)$$

and we assume

$$\sigma_{s1} = 4.80 \times 10^{-24}\ \text{cm}^2 \quad (29)$$

From Eqs. 27, 28, and 29, we have

$$\frac{\sigma_{t1}\xi}{(\int\sigma_0 dE/E)_{eff}} = \frac{0.0819}{1 + \dfrac{0.282}{a/\text{cm}}} \quad (30)$$

Taking the density of uranium as 18.9 gm/cm³, and that of graphite as 1.60 gm/cm³, we have $N_0 = 0.0478 \times 10^{24}$ atoms/cm³ and $N_1 = 0.0803 \times 10^{24}$ atoms/cm³. Using these values in Eq. 26, substituting from Eq. 30, and expressing V_1/V_0 in terms of a, b, and c, we obtain finally

$$T = \frac{b^2 - c^2}{a^2} \frac{0.1375}{1 + \dfrac{0.282}{a/\text{cm}}} G_0(\kappa'_0 a) + X_1(\kappa'_1 c, \kappa'_1 b) \quad (31)$$

For κ'_0 we use

$$\kappa'_0 = 0.0222 \frac{\text{density of uranium}}{\text{gm cm}^{-3}}$$

or, taking the uranium density to be 18.9 gm/cm³ we get $\kappa'_0 = 0.420$ cm^{-1}. For κ'_1 we use $\kappa'_1 = 0.1075$ cm^{-1}.

To illustrate the calculation of the resonance escape probability, we give numerical values from a sample calculation for $a = 1.0$ cm, $c - a = 1.0$ cm, $t = 0.115$ cm, and $b = 9.0$ cm. The results are

$$\frac{b^2 - c^2}{a^2} \frac{0.1375}{1 + \dfrac{0.282}{a/\text{cm}}} G_0(\kappa'_0 a) = 8.44$$

$$X_1(\kappa'_1 c, \kappa'_1 b) = 0.39$$

$$T = 8.44 + 0.39 = 8.83$$

$$p = e^{-1/T} = e^{-1/8.83} = e^{-0.1133} = 0.8930$$

Value of $k - 1$

The value of k is obtained as the product $\eta\epsilon pf$. A computational accuracy of at least 1 part in 10^3 was retained in each factor so as to obtain an accuracy of about 2% in $k - 1$.

As an illustration of the contribution of the several factors to k, we quote the numerical values in a sample calculation for $a = 1.0$ cm, $c - a = 1.0$ cm, $t = 0.115$ cm, and $b = 9.0$ cm. The results are $\eta = 1.308$, $\epsilon = 1.0225$, $p = 0.8930$, $f = 0.8834$, $k = \eta\epsilon pf = 1.0548$, and $k - 1 = 0.0548$.

Slowing Down Length

We use the symbol V to denote volume and we use the following subscripts: t for total, 0 for uranium, 1 for graphite, 2 for aluminum, and 3 for air gap. Thus

$$V_t = V_0 + V_1 + V_2 + V_3 \quad (32)$$

In the absence of any air gap we assume

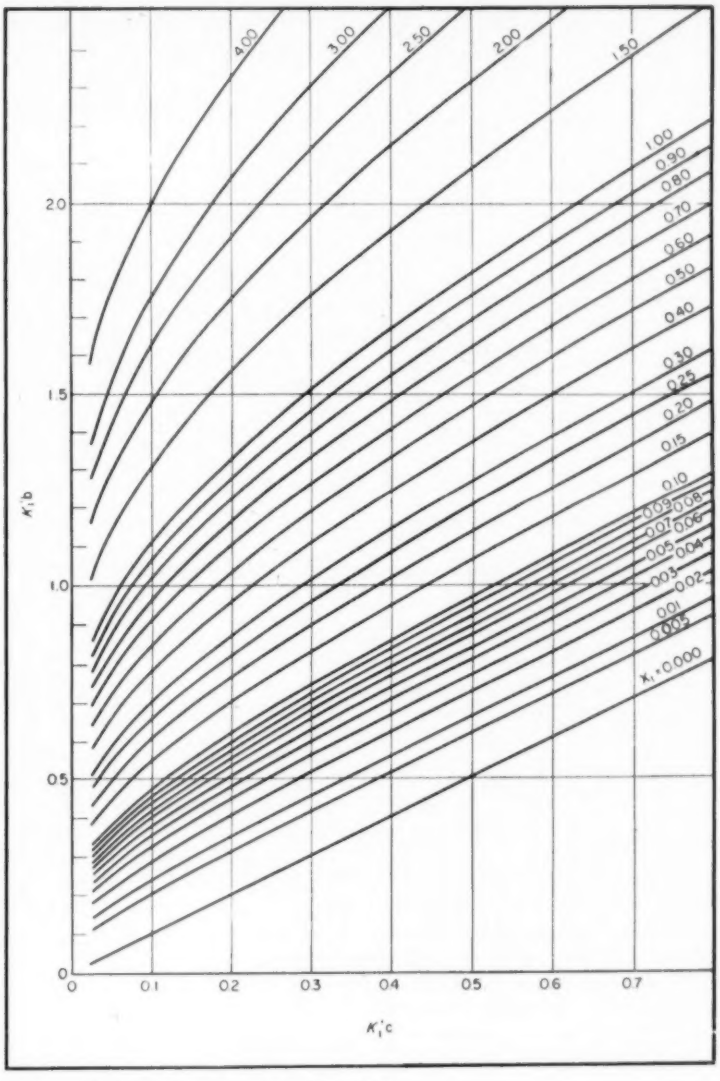

FIG. 7. Contours of the function $X_1(\kappa'_1 c, \kappa'_1 b)$

(declassified experimental results) that the square of the slowing down length has the value $387(V_t/V_1)$ cm² for neutrons which escape from the rod without making an inelastic collision, and $231(V_t/V_1)$ cm² for neutrons which make an inelastic collision before escaping from the rod.

Moreover, the fraction of neutrons which make an inelastic collision before escaping from the rod is (see the section on fast fission factor) approximately $(\sigma_i/\sigma_t)P$, where σ_i is the inelastic cross section for fission neutrons, σ_t is the total cross section for fission neutrons, and P is the probability that a fission neutron makes a collision before escaping from the rod.

Thus, in the absence of any air gap, we have

$$\frac{L_s^2}{\text{cm}^2} = \frac{V_t}{V_1}\left\{387\left(1 - \frac{\sigma_i}{\sigma_t}P\right) + 231\frac{\sigma_i}{\sigma_t}P\right\} = \frac{V_t}{V_1}\left\{387 - 156\frac{\sigma_i}{\sigma_t}P\right\} = \frac{V_t}{V_1}\{387 - 90P\} \quad (33)$$

assuming $\sigma_i/\sigma_t = 2.47/4.3$ as in the section on the fast fission factor.

To take account of the gap, we introduce an extra factor written as

$$\frac{V_t}{V_t - V_3} = \frac{V_t}{V_0 + V_1 + V_2} \quad (34)$$

so that

$$\frac{L_s^2}{\text{cm}^2} = \frac{V_t^2}{V_1(V_0 + V_1 + V_2)}\{387 - 90P\} \approx \left(\frac{V_t}{V_1 + (\frac{1}{2})V_0}\right)^2 \{387 - 90P\} \quad (35)$$

when $V_2 \ll V_0 \ll V_1$.

Finally, in terms of the rod radius, a, the outer radius, c, of the gap, and the radius, b, of the equivalent cell, we have

$$\frac{L_s^2}{\text{cm}^2} = \left(\frac{b^2}{b^2 - c^2 + (\frac{1}{2})a^2}\right)^2 \{387 - 90P\} \quad (36)$$

where P is the function of a shown in Fig. 2.

We conclude with a typical numerical example for $a = 1.0$ cm, $c - a = 1.0$ cm, $t = 0.115$ cm, and $b = 9.0$ cm. The results are

$$\left(\frac{b^2}{b^2 - c^2 + (\frac{1}{2})a^2}\right)^2 = 1.092$$

$$P = 0.212$$

$$L_s^2 = 1.092(387 - 90 \times 0.212) = 402 \text{ cm}^2$$

Diffusion Length

As in the previous section, we use V to denote volume and the subscripts t, 0, 1, 2, and 3 to denote total, uranium, graphite, aluminum, and air, respectively. We further use the symbol C with appropriate subscript to denote the fraction of thermal neutrons captured by the respective material, so that

$$C_0 + C_1 + C_2 = 1 \quad (37)$$

In this notation, the thermal utilization factor, f, is

$$f = C_0 \quad (38)$$

and the total competitive absorption is

$$\frac{1}{f} - 1 = \frac{C_1 + C_2}{C_0} \quad (39)$$

Thus C_0, C_1, and C_2 are quantities which have already been evaluated in computing f.

In the absence of any air gap, the formula assumed for the diffusion length, L, is

$$L^2 = 2{,}500C_1(V_t/V_1) \text{ cm}^2 \quad (40)$$

where 50 cm is the value assumed for the diffusion length in pure graphite.

To take account of the gap, we introduce a further factor

$$\frac{V_t}{V_t - V_3} = \frac{V_t}{V_0 + V_1 + V_2} \quad (41)$$

so that

$$\frac{L^2}{\text{cm}^2} = 2{,}500C_1\frac{V_t^2}{V_1(V_0 + V_1 + V_2)} \approx 2{,}500C_1\left(\frac{V_t}{V_1 + (\frac{1}{2})V_0}\right)^2 \quad (42)$$

when $V_2 < V_0 \ll V_1$

In the notation of the section on thermal utilization

$$C_1 = (R_1 + S_1 + B_1) = \{R_1 + X_1 + (X_1R_2 + B_1)\}f \quad (43)$$

or, neglecting unimportant terms,

$$C_1 \approx (R_1 + X_1)f \quad (44)$$

We thus obtain, with sufficient accuracy,

$$\frac{L^2}{\text{cm}^2} = 2{,}500(R_1 + X_1)f \times \left(\frac{b^2}{b^2 - c^2 + (\frac{1}{2})a^2}\right)^2 \quad (45)$$

where R_1, X_1, and f are obtained from the section on thermal utilization. We conclude with a sample numerical calculation for $a = 1.0$ cm, $c - a = 1.0$ cm, $t = 0.115$ cm, and $b = 9.0$ cm. The results are $R_1 = 0.1082$, $X_1 = 0.0137$, $X_1R_2 = 0.0001$, $B_1 = 0.0004$, $R_1 + X_1 = 0.122$, $f = 0.883$, and

$$\left(\frac{b^2}{b^2 - c^2 + (\frac{1}{2})a^2}\right)^2 = 1.092$$

From these values, we get

$$L^2 = 2{,}500 \times 0.122 \times 0.883 \times 1.092 = 294 \text{ cm}^2$$

Laplacian and Radius

The migration length, M, is related to the slowing down length, L_s, and the diffusion length, L, by $M^2 = L_s^2 + L^2$.

For the Laplacian, κ^2 (not to be confused with κ_0^2 or κ_1^2), we use the one-group formula

$$\kappa^2 = (k - 1)/M^2 \quad (46)$$

In the absence of a reflector, the radius, R_0, of a pile with height equal to diameter is given by

$$R_0 = 2.873\kappa^{-1} \quad (47)$$

In a typical example for $a = 1.0$ cm, $c - a = 1.0$ cm, $t = 0.115$ cm, and $b = 9.0$ cm, we get $L_s^2 = 402$ cm^2, $L^2 = 294$ cm^2, $M^2 = 696$ cm^2, $k - 1 = 0.0548$, $\kappa^2 = 0.0548/696 = 7.86 \times 10^{-5}$ cm^{-2}, $\kappa^{-1} = 1.13$ m, and $R_0 = 3.24$ m.

Reflector

For the theory of reflectors, the reader is referred to Glasstone and Edlund (7). There are alternative approximate formulas of various degrees of accuracy and complexity. For our present purpose, we choose the simplest one-group approximation, according to which, in a graphite pile, the radius, R_r, with a graphite reflector is related to the radius, R_0, without a reflector by $R_r = R_0 - L$, where L is the diffusion length in graphite. Using the value $L = 50$ cm, this becomes

$$R_r = R_0 - 0.50 \text{ m} \quad (48)$$

The saving in radius due to a reflector as calculated on the more accurate two-group model is somewhat greater than the saving calculated on the one-group model. In a particular sample calculation on the two-group model, the reduction in radius due to the reflector was found to be 58 cm, as compared with the 50 cm used by us. We conclude that our estimates are pessimistic.

Rods and Uranium

If ρ_U denotes the density of uranium, then the mass of a single rod of radius a and length $2R_r$ is

$$2\pi\rho_U a^2 R_r \quad (49)$$

Now, according to the definition of b, the radius of a cell, the cross sectional area per rod is πb^2. Hence the number, N, of rods in a pile of total cross section πR_r^2 is

$$N = R_r^2/b^2 \quad (50)$$

The total mass of uranium, obtained by multiplying Eq. 49 by Eq. 50, is

$$U = 2\pi\rho_U (a^2/b^2) R_r^3 \quad (51)$$

Then, assuming $\rho_U = 18.9$ tons/m^3,

$$\frac{U}{\text{tons}} = 119\frac{a^2}{b^2}\left(\frac{R_r}{\text{meters}}\right)^3 \quad (52)$$

In a sample numerical example for $a = 1.0$ cm, $c - a = 1.0$ cm, $t = 0.115$ cm, and $b = 9.0$ cm, the results are $R_r = (3.24 - 0.50) = 2.74$ m, $N = (274/9)^2 = 930$, and $U = (119/81)(2.74)^3 = 30.5$ tons.

Results

The results of the calculations are given in the table on the next page for each combination of the four alterna-

Results of the Calculations for Rods Sheathed with 1.15 mm of Aluminum

b (cm)	f	p	$k-1$	κ^2 (m^{-2})	R_r (m)	N	U (tons)
a = 0.75 cm, $c-a$ = 0 cm							
6.0	0.902	0.860	0.0312	0.524	3.47	3,345	77.6
6.5	0.888	0.880	0.0392	0.621	3.15	2,349	49.3
7.0	0.873	0.896	0.0405	0.606	3.19	2,077	44.2
7.5	0.858	0.909	0.0379	0.535	3.42	2,079	47.4
7.75	0.850	0.915	0.0341	0.469	3.69	2,267	55.8
8.0	0.842	0.920	0.0299	0.400	4.04	2,550	68.8
a = 0.75 cm, $c-a$ = 1 cm							
6.0	0.911	0.848	0.028	0.423	3.92	4,280	112
6.25				0.511	3.52	3,190	74
6.5	0.898	0.870	0.039	0.575	3.28	2,560	56
6.75				0.610	3.18	2,210	47
7.0	0.883	0.889	0.0445	0.625	3.12	1,980	41.5
7.25				0.613	3.16	1,900	40
7.5	0.867	0.9035	0.044	0.585	3.25	1,880	41
7.75				0.546	3.38	1,900	43
8.0	0.853	0.915	0.0385	0.496	3.58	2,000	48
8.25				0.436	3.85	2,190	56
8.5				0.370	4.22	2,480	70
9.0	0.821	0.933	0.019	0.227	5.54	3,800	140
a = 0.75 cm, $c-a$ = 2 cm							
6.0	0.922	0.8245	0.011	0.130	7.45		
6.5	0.909	0.854	0.032	0.385	4.13	6,380	176
7.0	0.8945	0.876	0.043	0.521	3.47	2,450	57
7.25				0.545	3.39	2,190	49.5
7.5	0.880	0.894	0.0465	0.549	3.37	2,030	46
7.75				0.537	3.42	1,950	44.5
8.0	0.865	0.908	0.0445	0.514	3.50	1,920	45
8.25				0.475	3.67	1,990	49
8.5			0.038	0.429	3.90	2,110	55
9.0	0.833	0.928	0.029	0.312	4.64	2,650	82
a = 1 cm, $c-a$ = 0 cm							
7.0	0.917	0.837	0.027	0.483			
8.0	0.896	0.874	0.047	0.769	2.78	1,210	40
8.5	0.884	0.887	0.048	0.746	2.82	1,100	37
9.0	0.872	0.899	0.049	0.725	2.88	1,025	36
10.0	0.846	0.918	0.039	0.532	3.44	1,180	48
11.0	0.820	0.932	0.022	0.274	5.0	2,070	123
12.0	0.7925	0.943					
a = 1 cm, $c-a$ = 1 cm							
7.5			0.036	0.579	3.28	1,910	74.5
8.0	0.906	0.864	0.047	0.717	2.90	1,320	46
8.5			0.053	0.780	2.75	1,050	34.5
9.0	0.883	0.893	0.055	0.786	2.74	930	30.5
9.5			0.054	0.740	2.84	890	30
10.0	0.859	0.913	0.050	0.664	3.01	910	32.5
10.5			0.043	0.559	3.34	1,010	40
11.0	0.833	0.929	0.035	0.435	3.90	1,260	58.5
11.5			0.0255	0.304	4.71	1,680	94
12.0	0.807	0.940	0.015	0.1715			
a = 1 cm, $c-a$ = 2 cm							
8.0	0.915	0.850	0.041	0.551	3.35	1,750	70
8.5			0.051	0.680	2.98	1,230	43.5
9.0	0.893	0.884	0.056	0.737	2.845	1,000	34
9.5			0.057	0.734	2.85	900	30.5
10.0	0.870	0.908	0.055	0.687	2.95	870	30.5
10.5			0.051	0.613	3.17	910	34.5
11.0	0.8445	0.9245	0.044	0.522	3.50	1,010	42
11.5			0.036	0.409	3.99	1,200	57
12.0	0.8185	0.937	0.026	0.286	4.9	1,670	97

b (cm)	f	p	$k-1$	κ^2 (m^{-2})	R_r (m)	N	U (tons)
a = 1.25 cm, $c-a$ = 0 cm							
9.0	0.906	0.857	0.0440	0.747	2.82	985	51.6
9.5	0.897	0.871	0.0502	0.819	2.68	793	39.3
10.0	0.887	0.884	0.0532	0.834	2.65	700	34.4
10.5	0.876	0.894	0.0533	0.804	2.70	663	33.3
11.0	0.866	0.903	0.0513	0.743	2.83	663	34.8
11.5	0.855	0.912	0.0471	0.656	3.05	702	39.7
12.0	0.843	0.919	0.0415	0.557	3.35	779	48.5
a = 1.25 cm, $c-a$ = 1 cm							
9.5			0.052	0.820	2.67	790	39
10.0	0.898	0.8755	0.057	0.862	2.595	672	32.5
10.5			0.059	0.874	2.57	599	28.5
11.0	0.878	0.898	0.059	0.850	2.615	562	27
11.5			0.057	0.790	2.73	564	28.5
12.0	0.857	0.914	0.053	0.709	2.90	580	31
12.5			0.047	0.610	3.18	647	38
13.0	0.835	0.927	0.040	0.502	3.55	742	49
13.5			0.032	0.385	4.13	936	72
14.0	0.812	0.937	0.023	0.272	5.0	1,270	118
a = 1.25 cm, $c-a$ = 2 cm							
10.0	0.907	0.866	0.055	0.781	2.75	752	38.5
10.5			0.060	0.835	2.64	632	31
11.0	0.888	0.8905	0.0625	0.845	2.625	568	28
11.5			0.062	0.821	2.67	540	27
12.0	0.8675	0.9085	0.060	0.769	2.78	535	27.5
12.5			0.055	0.693	3.95	557	30.5
13.0	0.846	0.923	0.0495	0.604	3.19	600	35.5
13.5			0.0425	0.503	3.55	691	45.5
14.0	0.824	0.934	0.0345	0.397	4.0	822	61
a = 1.5 cm, $c-a$ = 0 cm							
11.0	0.894	0.869	0.048	0.773	2.76	630	46.5
11.5	0.884	0.880	0.051	0.799	2.715	558	40.5
12.0	0.875	0.892	0.054	0.810	2.69	502	36
12.5	0.865	0.901	0.052	0.756	2.80	502	37.5
13.0	0.856	0.908	0.049	0.684	2.96	515	40.5
14.0	0.835	0.921	0.038	0.500	3.55	645	61
15.0	0.814	0.928					
a = 1.5 cm, $c-a$ = 1 cm							
11.5			0.058	0.891	2.54	488	33
12.0	0.868	0.885	0.060	0.893	2.54	450	30.5
12.5			0.060	0.871	2.58	426	29.5
13.0	0.869	0.902	0.059	0.826	2.66	418	30
13.5			0.056	0.756	2.80	430	32
14.0	0.850	0.916	0.051	0.673	3.00	459	37
14.5			0.045	0.578	3.28	512	45
15.0	0.830	0.927	0.038	0.476	3.66	595	58.5
15.5			0.031	0.371	4.22	741	84
16.0	0.809	0.936	0.023	0.266			
a = 1.5 cm, $c-a$ = 2 cm							
11.5			0.059	0.877	2.57	499	34.5
12.0	0.898	0.877	0.063	0.893	2.54	450	30.5
12.5			0.064	0.889	2.55	416	28.5
13.0	0.880	0.896	0.064	0.8695	2.58	394	27
13.5			0.063	0.830	2.65	385	27.5
14.0	0.861	0.911	0.060	0.769	2.78	394	29
14.5			0.055	0.696	2.94	411	32.5
15.0	0.842	0.923	0.049	0.602	3.19	452	38.5
15.5			0.0425	0.504	3.55	525	50
16.0	0.822	0.933	0.035	0.404	4.0	625	67

tives $a = 0.75$, 1.0, 1.25, and 1.50 cm, with the three alternatives $c - a = 0$, 1.0, and 2.0 cm. The quantities tabulated are b, the radius of the equivalent cell; f, the thermal utilization factor; p, the resonance escape factor; $k - 1$, where k is the reproduction constant; κ^2, the Laplacian; R_r, the critical radius; N, the number of rods; and U, the critical quantity of uranium. All these results apply to rods with an aluminum sheath 1.15 mm thick. The same data are reproduced in Figs. 8 and 9, which give contours of $k - 1$ and U, respectively, as functions of b and a.

For each pair of values of a and c, the main object of varying b is to determine what value of b leads to a minimum value of U. This value of b is, for brevity's sake, referred to as the optimum, and is plotted against a in Fig. 10. For most purposes, data for a pile of optimum b for the given a, c, and t are of greater importance and interest than those for other values of b for the same a, c, and t. The data relating to such piles with optimum b are therefore presented in the form of curves in which various quantities are plotted against a, for stated values of $c - a$, all at optimum b. The quantities $(b^2 - c^2)/a^2$, k, M^2, κ^2, R_r, N, and U are also so plotted in Fig. 10.

Our calculations give a fairly comprehensive picture of the effect of varying both the rod radius, a, and the radius, b, of the equivalent cell of moderator. The reproduction factor, k, and the Laplacian, κ^2, each have a maximum, while the critical tonnage, U, has a minimum.

The calculations show that the variation of $k - 1$ with a, for values of b chosen to give $k - 1$ its maximum value, is quite slow over the range from

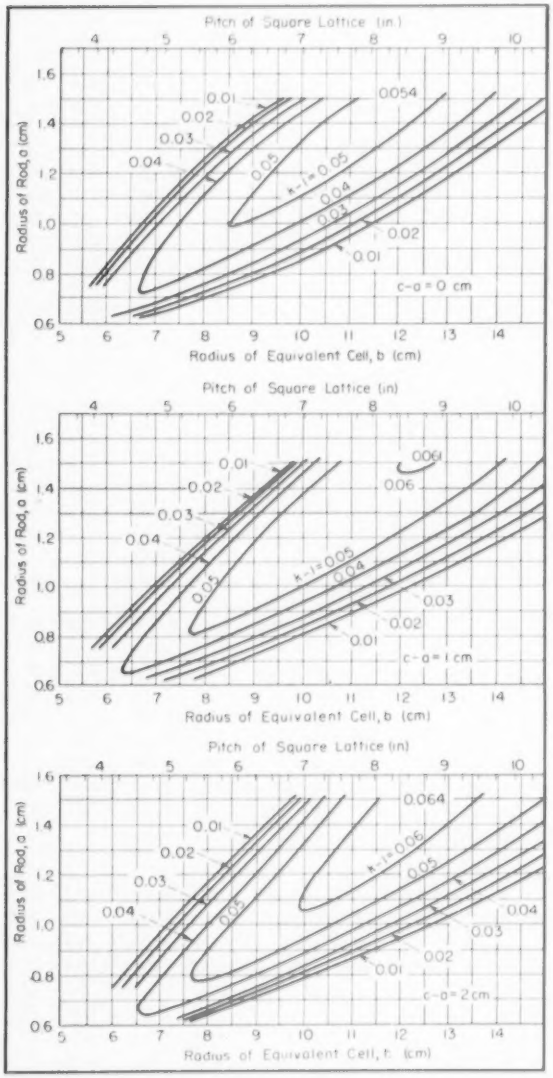

FIG. 8. Contours of $k - 1$ for three air gaps and a 1.15-mm aluminum sheath

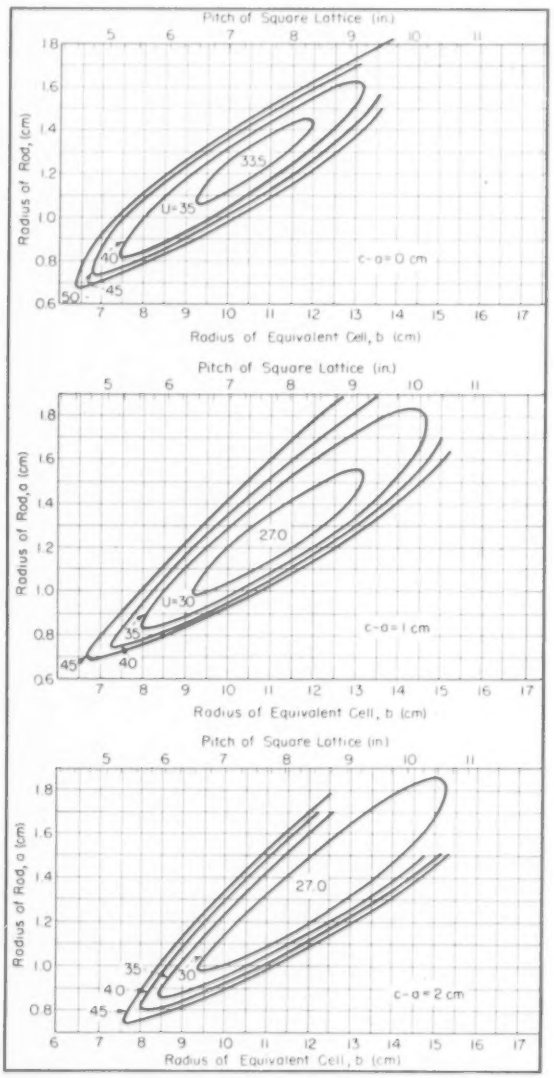

FIG. 9. Contours of uranium tonnage, U, for three air gaps and a 1.15-mm aluminum sheath

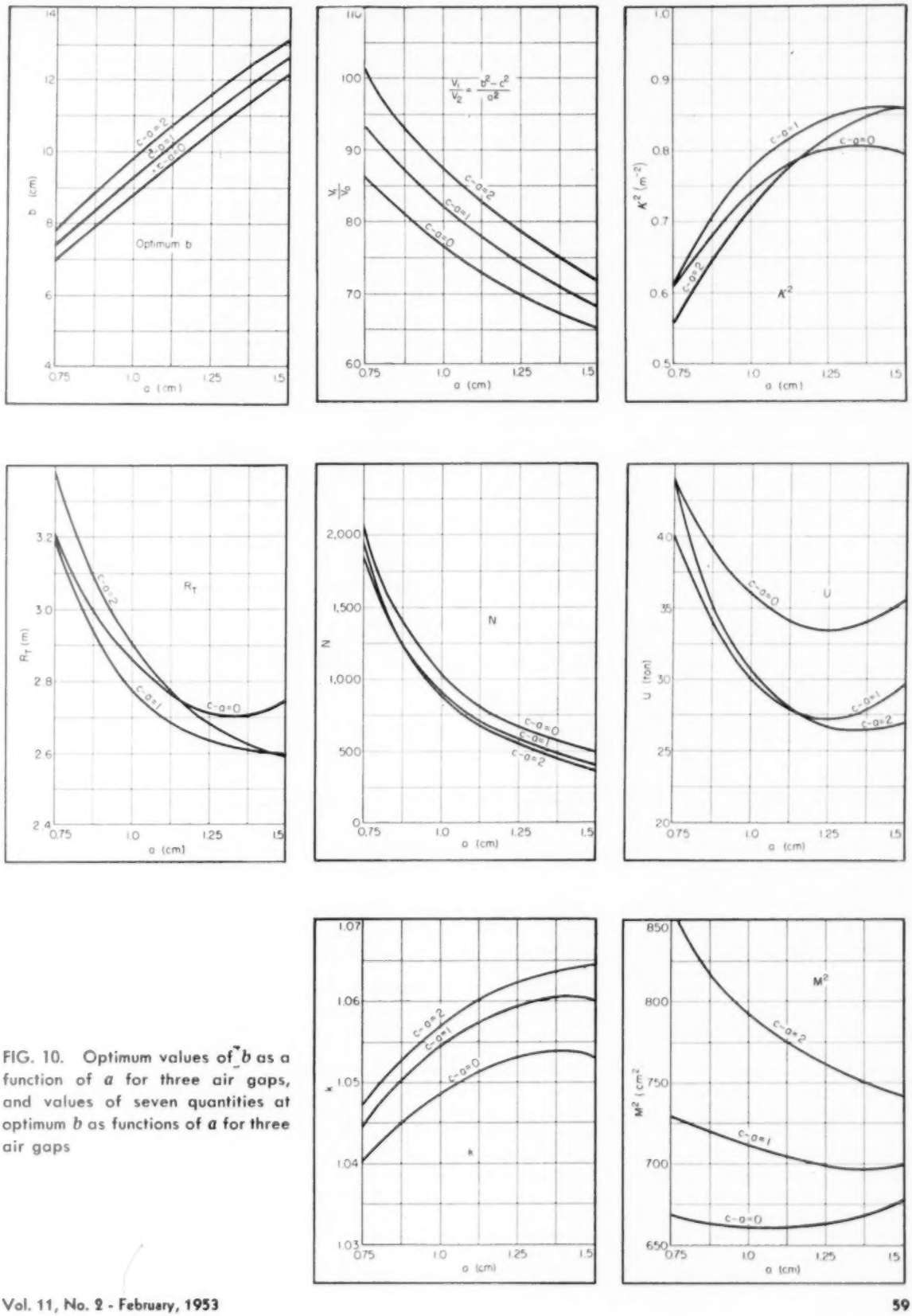

FIG. 10. Optimum values of b as a function of a for three air gaps, and values of seven quantities at optimum b as functions of a for three air gaps

$a = 0.75$ to $a = 1.50$ cm, with a flat maximum near $a = 1.50$ cm. The calculated value of k for thick rods ($a > 2.0$ cm) is sensitive to the constants chosen in the calculation of the fast fission factor, ϵ. Since the experimental basis for these constants is questionable, the conclusions on the variation of $k - 1$ with a for thick rods are untrustworthy.

The Laplacian, κ^2, varies in much the same way as $k - 1$, but reaches its maximum at slightly smaller values of a and b, and decreases more rapidly with a for thick rods (b being varied with a to make κ^2 a maximum).

The critical tonnage, U, depends much more critically on a and b than do k and κ^2. The minimum ("optimum") values are in the region $a = 1.25 \pm 0.25$ cm and $b = 11.0 \pm 1.5$ cm, depending somewhat on the width of the air gap, $c - a$. For a cylindrical pile with height equal to diameter, composed of uranium rods sheathed in 1.15 mm of aluminum, arranged as a lattice in a graphite moderator and surrounded by a graphite reflector, the minimum quantity of uranium required appears to be about 26 tons.

The effect of varying the air gap is far from negligible, as may be seen from Figs. 8–10. Increase of the air gap results in an increase of both $k - 1$ and the migration area, M^2. In general, the Laplacian, κ^2, increases, reaches a maximum, and then decreases, and the critical tonnage first decreases, reaches a minimum, and then increases.

The optimum values of a, b, and $c - a$ for minimum tonnage ($U = 26$ tons) resulting from the calculations are $a = 1.25$ cm (± 0.10 cm), $b = 11.5$ cm (± 0.50 cm), and $c - a = 1.5$ cm (± 0.25 cm).

The effect of the gap can be traced to its effect on the thermal utilization factor, f. The depression of the neutron density inside the air space below the mean level in the graphite, shown in Figs. 3 and 6, arises from the density gradient associated with the flux of neutrons into the uranium. If the outer radius of the air space is increased, this flux is distributed over a bigger area, and the density gradient is thereby reduced. This in turn results in a raising of the neutron density in the air space and consequently in a raising of the thermal utilization. A corresponding effect on the number of resonance neutrons captured in uranium, which would reduce p, is much smaller because of the much more uniform distribution of resonance neutrons in the graphite of the reactor.

In a homogeneous pile, the various quantities of interest would essentially depend only on the proportion of uranium to graphite. In our arrangement, this is effectively measured by the volume ratio $(b^2 - c^2)/a^2$. This is plotted for the optimum lattice against a, with $c - a$ as a parameter in Fig. 10. It will be noticed that this ratio remains moderately constant; the value for the optimum combination of a, b, and $c - a$ is $(b^2 - c^2)/a^2 = (11.5^2 - 2.75^2)/(1.25^2) = 80$.

Two useful empirical rules for optimum lattices, where b is adjusted to minimize U for given values of a and $c - a$, are the following. The thermal utilization factor, f, and the resonance escape factor, p, are equal to within 1%. The migration length is independent of a to within 10%.

* * *

We are greatly indebted to Mr. M. Goldstein and Mrs. J. Laird for numerous calculations and graphs.

This Article is based on report R/R 922 (Atomic Energy Reshearch Establishment, Harwell). Original references have been changed to refer to material more readily available in this Country.

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lacking further evidence, to associate most of these with one or the other of the particles mentioned below.

The χ-Meson and Others

A particle of mass 1,000–1,500 m_e has been seen to stop in photographic emulsions and decay into a π-meson of unique kinetic energy (≈ 115 Mev) and, therefore, a single neutral particle. The neutral particle is at least as heavy as the π^0, and possibly as heavy as the V_2^0. The MIT group has observed particles which stop in a plate in a cloud chamber and emit a π-meson of apparently the same unique energy (the S-particle). These are probably the same χ-mesons. Many observers have reported the decay in flight of charged V-particles, also probably mostly χ-mesons. The decay scheme is $\chi^{\pm} \rightarrow \pi^{\pm} +$ a heavier neutral, with a mean life between 2×10^{-8} and 2×10^{-9} sec. The neutral decay product may be a neutral τ-meson, which decays into 2 γ-rays, or alternatively, the V_2^0.

The κ-Meson

A particle has been observed in nuclear emulsions which decays, after stopping, into a μ-meson and two (or more) neutral particles (the decay μ-meson momentum varies up to $\sim$300 Mev/c). The mass of the κ-meson is $>1{,}000\ m_e$. A tentative decay scheme is $\kappa^{\pm} \rightarrow \mu^{\pm} + 2\nu$. The similarity to the μ-meson decay tempts one to speculate about the possibility that there may be a family of electron-like particles, of which the electron, μ-meson, and κ-meson are the ones that have so far been observed.

The Bristol group has accumulated considerable evidence for direct and copious production of χ- and κ-mesons (lumped together under the name K-meson) in high-energy nuclear interactions. Whether these are all χ, or all κ, or both, or some other type altogether, it is too early to say, although there is evidence that at least some of the low-energy ones may be of the κ-meson type.

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The complete report of the proceedings of the conference will be published by Interscience Publishers, Inc., New York.

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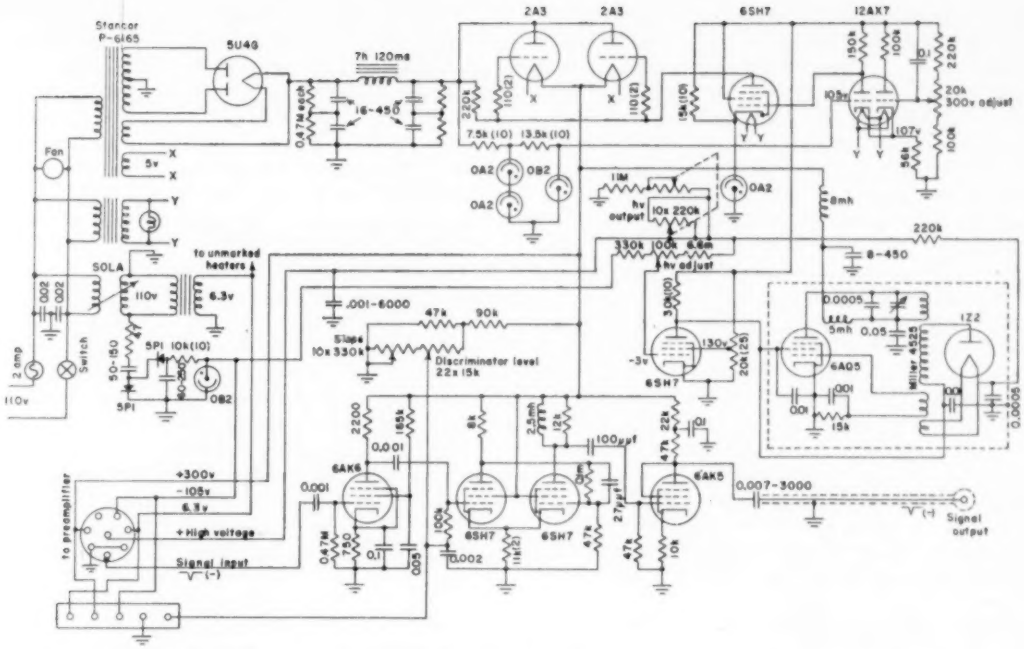

FIG. 1. Schematic diagram of power supply and discriminator unit

A Scintillation-Counter Power Supply Offering Long-Time Stability

To obtain statistically valid results at low counting rates, scintillation counters must be operated in the region where sensitivity is greatly dependent on dynode voltage. In the unit described, the net change in high voltage is limited to 0.077% in 22 hours. Long-term stability is proved by a year's operation

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ALTHOUGH commercial scintillation counters are widely used in low-level work, most of them have insufficient transient stability and long-time stability for this application. The output voltage regulation of commercial scintillation-counter power supplies is adequate to allow satisfactory operation at high counting rates because almost all photomultiplier tubes exhibit sensitivity plateaus. On such a plateau, changes in the dynode voltage within the usual limits of regulation will not cause large changes in the source counting rate.

But while the signal-to-noise ratio may be large in this region, constant background rates are unattainable. Thus, to provide statistically accurate data, the source counting rate should be at least 50,000 cpm. For biological work, with source counting rates of the

order of 4,000 cpm or less, operating on the plateau would not afford statistical accuracy in data taken over short counting periods.

In the region where the background rate is low enough to give accurate data, the photomultiplier sensitivity is greatly dependent on changes in dynode voltage. This article describes a power supply and discriminator unit designed to eliminate these difficulties in gathering accurate and comparable low-level data by providing the necessary over-all stability.

Power Supply Design

Regulation of all output voltages of the supply improves the long-time counting stability and eliminates variations due to transient line-voltage fluctuations. The voltage requirements of a scintillation counter are (1) an a-c heater supply, (2) a 300-volt plate supply, (3) a 100-volt negative bias supply, and (4) an adjustable 1,600-volt dynode supply.

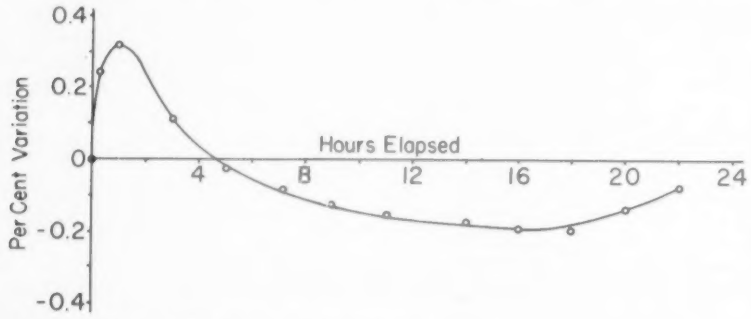

FIG. 2. Time variation of high-voltage output

Heater supply. One problem in designing the scintillation counter for low-level work is stabilizing the sensitivity of the pulse amplifier and the amplitude discriminator. The line voltage variation over a 24-hr period is large enough to affect the cathode emission of these stages and, consequently, their sensitivity. In this design, a Sola voltage regulating transformer supplies primary voltage to the discriminator heater transformer. See Fig. 1. A 30% change in line voltage causes less than 1% change in heater voltage.

Plate supply. The 300-volt plate supply shown in Fig. 1 is a special modification of a conventional design with two parallel 2A3's added in series with the supply voltage. Besides these tubes, the other stabilizing elements are the reference voltage circuit and the difference amplifier.

Because their output voltage is temperature dependent, voltage regulator tubes are usually unsatisfactory as voltage references for a closely-regulated supply. Current changes through these tubes normally cause them to operate with drifting temperatures and to put out changing voltages which would in turn be amplified and translated into fluctuations in the 300-volt output. Figure 1 shows how this difficulty was overcome by using a network of resistances and VR-tubes supplied by the unregulated filter output. Two series OA2's furnish a stabilized voltage. From their output, current passes through a bleeder resistor and through an OB2, which furnishes the reference voltage free from the effect of a variable supply-voltage source.

Current discontinuities in the VR tubes cause reference voltage variations up to 0.3 volt when average operating currents of less than 10 or 12 ma are used. Currents of 15 ma or more eliminate this trouble, although a few VR tubes give a fluctuating output voltage even at this current. The final design of the VR circuit allows as large a tolerance to line voltage variations as possible between the limits of exceeding the maximum VR current rating and experiencing current discontinuities. This arrangement also minimizes output voltage changes due to all causes other than external temperature variations.

The difference amplifier shown in Fig. 1 consists of a 6SH7 in cascade with a 12AX7. The cathodes of the 12AX7 are connected through a common high resistance to ground, so that a given change in plate current of one triode section will cause an opposite and nearly equal change in the plate current of the other section.* This stage compares the difference between the reference voltage described and a given part of the regulated 300-volt output. The 6SH7 further amplifies the difference voltage and controls the effective resistance of the two easily obtained 2A3 rheostat tubes.

An OA2 raises the cathode voltage of the 6SH7 and places its grid bias in the normal operating range. To avoid current discontinuities in the OA2, part of its current is supplied from a 13,000-ohm resistor connected to the regulated 300-volt output. To increase the maximum plate voltage of the 6SH7, its plate-load resistor connects to the unregulated side of the supply. This reduces the over-all regulation slightly, but widens the range of input voltage tolerance by maintaining a larger current through the 6SH7 when the grid voltage of the 2A3's approaches that of their filaments.

Bias supply. Selenium rectifiers in a voltage-doubling circuit connected across the output of the Sola transformer furnish a negative bias voltage. An OB2 tube regulates the bias output at 105 volts. Using the Sola output for this supply eliminates the temperature-dependence component of the OB2's output voltage by keeping the doubled voltage within a 1% tolerance.

High-voltage supply. Although it is possible to build regulating circuits for conventional power supplies with output voltages in the kilovolt range, they are not satisfactory for scintillation counter use.* Brush discharges in the transformer cause high-frequency transients that may be picked up by the pulse amplifier. Thus, a radio-frequency high-voltage supply is used.

A 6AQ5 oscillator operating at about 200 kc furnishes a voltage which is stepped up by a radio-frequency transformer. The rectifier is a 1Z2; radio-frequency current heats its filament. A simple RC network filters the rectified r-f voltage. The frequency drift of the r-f circuit is minimized by using a negative temperature coefficient capacitor across the transformer primary.

Although the plate voltage and the heater voltage to the 6AQ5 oscillator are both regulated, some extra stabilization of the high-voltage output is necessary to minimize changes due to

* W. C. Elmore, M. Sands, "Electronics—Experimental Techniques," National Nuclear Energy Series V-1 (McGraw-Hill Book Co., Inc., New York, 1949).

long-time thermal effects. A 6SH7 shown in the circuit diagram amplifies a fraction of the 1,600-volt output and controls the screen voltage of the 6AQ5 oscillator. In addition, the voltage drop across the 6SH7 is in series with the high-voltage output. The high-voltage regulation is partly dependent on the bias voltage, because this is connected to the high-voltage feedback loop.

A dual potentiometer in a constant-current circuit controls the voltage to the dynodes and keeps the grid voltage of the regulating amplifier within the normal operating range when the high-voltage output is adjusted. A tap switch is used in the potentiometer to make high-voltage output settings instantly reproducible.

Amplifier and Discriminator

The signal from the photomultiplier preamplifier goes through an amplifier built into the supply. A Schmitt amplitude discriminator using two 6SH7's (Fig. 1) furnishes a uniform output pulse height so that the net counting rate is not dependent on the pulse-height sensitivity of the scaler. The load resistor of the discriminator is critically compensated to extend the range of output linearity. A 6AK5 phase inverter following the discriminator gives the scaler a negative input pulse.

Physical Layout and Ventilation

The compactness desirable in a unit such as the one described here poses the problem of minimizing output voltage drift due to internal heating of the temperature-dependent parts. Air holes allow ventilation, and metal legs hold the bottom of the cabinet 2 in. above the supporting table. An induction type fan provides forced air circulation and keeps the inside temperature of the unit below 50° C.

In placing the temperature-dependent parts, the resistors in the control circuits must be given as much ventilation as possible. The VR tubes should be mounted on the corner of the chassis farthest from the power transformer, and the r-f high-voltage supply placed directly under the fan.

Characteristics and Performance

Measurements were taken of the output impedance of the 300-v supply, the line-voltage regulation, the time stability, and the counting-rate stability.

Effective output impedance. The effective output impedance of a power supply, often used as a figure of merit, is defined as $Z_0 = \Delta E_0/\Delta I_0$. The measured Z_0 of the 300-volt supply is 0.33 ohm. The low output impedance helps to prevent count variations due to load changes and eliminates decoupling between amplifier stages.

Line voltage regulation. The regulation of the output voltages as a function of line voltage is as follows:

Output voltage	*Per cent variation for 1% line voltage variation*
1,600	0.0017
300	0.0032
105	0.0017

It is interesting to note that the high-voltage regulation is the same as that of the bias supply. As mentioned, the high-voltage stability depends largely on the bias-voltage stability.

The regulated heater voltage remains within a 1% tolerance throughout the operating range of the supply.

Time stability. The time variation of the d-c output voltages after a 1-min warm-up is as follows:

Output voltage	*Per cent change per hour*
1,600	0.32
300	0.038
105	0.032

After the first hour the internal temperature of the unit becomes steady, and the rates of change decrease.

Figure 2 shows the high-voltage time variation over a 22-hour period after a 1-min warm-up. The net change in high-voltage output over the 22-hr period is 0.077% or 1.3 volts, while the maximum variation of 0.32% occurs after 1 hr of operation. Further variations are apparently due to external thermal changes.

Counting-rate stability. A Co^{60} source, an anthracene phosphor, and a 5819 photomultiplier tube were used with the supply to determine its counting-rate stability over a 24-hr period. The counting rate was about 49,000 cpm, giving an expected statistical accuracy of the square root of 245,000 or about 0.2% for 5-min counts. The maximum variation in counting rate experienced was 0.2%, agreeing with the predicted error. A similar test was made six months later with the same source and equipment. After correction was made for source decay, the test showed no change in the counting rate.

Discussion

This power supply and discriminator unit has been used at the University of Minnesota Hospitals for more than a year without need of repairs or maintenance. Tap-switch settings reproduce the required high-voltage and discriminator level for a specific use. No change from the original settings for any given application has been required. High detection accuracy has been maintained in low-level biological work, such as brain tumor detection and thyroid uptake measurements.

HEAVY WATER: A NEUTRON PRODUCER

At congressional hearings for the Independent Appropriations Offices for 1951, the following discussion, on the AEC's need for a heavy-water plant, took place between Representative Albert Gore and AEC witnesses Lawrence R. Hafstad (director, division of reactor development) and Carleton Shugg (then deputy general manager):

HAFSTAD: . . . New products have been devised to make it possible to utilize an entirely new approach to the production of heavy water, getting it essentially as a byproduct of some other commercial processes handling large amounts of hydrogen. . . . Now, once this is done, heavy water can be used as more or less of an ordinary material instead of an unusual material in reactor designs, and for this reason we are beginning now to think of other types of reactors which will use this material. . . . The materials-testing reactor . . . uses large amounts of ordinary water, and . . . [the reactor's] usefulness as a neutron producer is limited, because ordinary water absorbs and eats up the neutrons. [In the new reactors being planned] we are going to use the neutron producer, heavy water, which is an especially valuable coolant.

GORE: The important thing here is whether or not this plant producing heavy water will result in a lessening of expense in some other way . . .

SHUGG: It will, in this way: that the ability to use this material more freely will increase the capacity of the units we are going to build, so that they will not have to be built as big as they would if they did not have this material. When Dr. Hafstad stated this increased the neutron-producing ability of the reactor, that means we can get the neutrons we are after.

CROSS SECTIONS

Preparation of a Tritiated Self-Luminescent Material

By IRVING A. BERSTEIN, WINIFRED BENNETT, MELVIN FIELDS,* and EARLE C. FARMER
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Many organic aromatic crystalline materials fluoresce under external ionizing radiation (*1*), and if the radiation is sufficiently intense, this fluorescence can be detected visually. Thus, it might be expected that a self-luminescent material could be obtained by incorporating a radioisotope into the molecule of one of these fluorescent compounds. Recently, it has been reported that anthracene labeled with carbon-14 of specific activity of 0.9 μc/mg glowed with a visible fluorescence after the observer was sufficiently dark adapted (*2*).

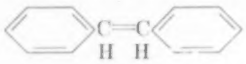
Our efforts have been directed toward the synthesis of a tritiated self-luminescent material which could be expected to have several significant advantages relative to phosphors activated by other radioisotopes:

1. Less hazard. Tritium-activated luminescent materials should be less hazardous in handling and shielding than phosphors activated with more energetic beta emitters or radium because of the extremely small range of the beta particles from tritium [0.6 mg/cm² for β_{max} (*3*)].

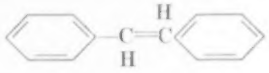
2. Constant luminosity. A much more constant luminosity can be expected for a tritiated phosphor than is presently available with phosphors activated by more energetic isotopes, particularly radium-activated phosphors. The latter undergo a continual loss in light output due to destruction of the phosphor by the densely-ionizing radiation.

3. Easier synthesis. Tritium-activated organic phosphors appear to be more feasible to synthesize than C^{14}-activated materials since the techniques of introduction of hydrogen into fluorescent organic compounds are more straightforward than those for C^{14}. Also, tritium is available in much higher specific activity and at much lower cost ($0.10/mc for tritium in the gaseous state and $36.00/mc for C^{14} in the form of $BaCO_3$).

The first tritiated self-luminescent material we prepared was *trans*-stilbene which was obtained by reduction with tritium of diphenylacetylene to *cis*-stilbene and subsequent isomerization by heat of the *cis*-stilbene to *trans*-stilbene. Isomerization is necessary since the *cis* form of the compound



exhibits no significant amount of fluorescence, whereas the *trans*-compound



has marked fluorescence (*4*).

Figure 1 is a transmission fluorescence spectrum of our tritiated *trans*-stilbene under mercury-arc excitation.† From considerations of work on fluorescence of aromatic crystalline compounds under various modes of excitation (*5–8*) (α, γ, X-rays, and ultraviolet light) it is believed that this fluorescence spectrum represents the scintillation light emitted by the tritiated *trans*-stilbene under excitation by tritium beta radiation.

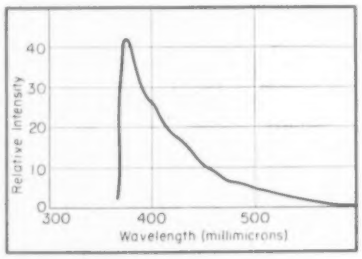


FIG. 1. Transmission fluorescence spectrum of tritiated *trans*-stilbene

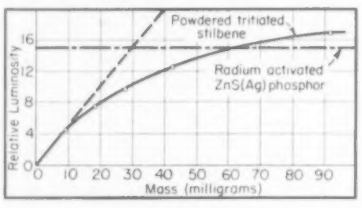


FIG. 2. Relative light output vs mass of tritiated *trans*-stilbene

The tritiation apparatus employed in this synthesis is a modification of one recently reported (*9*) which has been adapted for use in tritiations wherein small amounts of hydrogen (50 ml to a few hundred ml) are used. The procedure described on page 65 is of general utility for tritiation of organic compounds containing multiple bonds.

Reduction with Tritium

Into a 250-ml hydrogenation bottle were placed a solution of 1 gm diphenylacetylene in 7 ml of dry benzene and 0.05 gm of 1% palladium on calcium carbonate catalyst. The tritiations were carried out according to the procedure on page 65, using a 1-curie ampoule of tritium supplied by Oak Ridge National Laboratory. The reduction mixture was filtered through celite to separate the catalyst. The benzene solvent was then removed by distillation at about 20 mm pressure and heating at 50° C.

Radioanalysis of the benzene solvent showed no radioactivity and thus indicated no exchange had occurred with the solvent over the 1% palladium on calcium carbonate catalyst.

Isomerization by Heat

The liquid *cis*-stilbene obtained from the reduction reaction was pipetted into a bomb tube, frozen in liquid nitrogen, degassed, refrozen and sealed

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† Spectrum taken by Dr. Bernard Manning.

under vacuum. The tube was placed in a preheated furnace at 315° C for 1½ hr (*10*). On cooling, a mixture of white crystals and yellow solid resulted. The *trans*-stilbene was purified by chromatographic adsorption on alumina and elution with *n*-pentane. It was found that 0.67 gm of *trans*-stilbene was obtained; this represented a mass yield of 67%.

Tritium Analyses

Analyses for tritium were accomplished by combustion of the *trans*-stilbene on a semi-micro scale and conversion of the tritiated water to hydrogen (*11*), which was then counted in an ionization chamber with a Lindemann-Ryerson electrometer (*12*). The equivalence of rate of discharge of the electrometer (mv/sec) per millicurie of tritium gas was established with aliquots of tritium obtained by manometric dilution of several tritium ampoules of given activity as supplied by Oak Ridge. The radioanalyses indicated a specific activity of 360 mc/gm. The tritiated stilbene was also counted by the liquid scintillator technique (*13*).

Relative Light Output

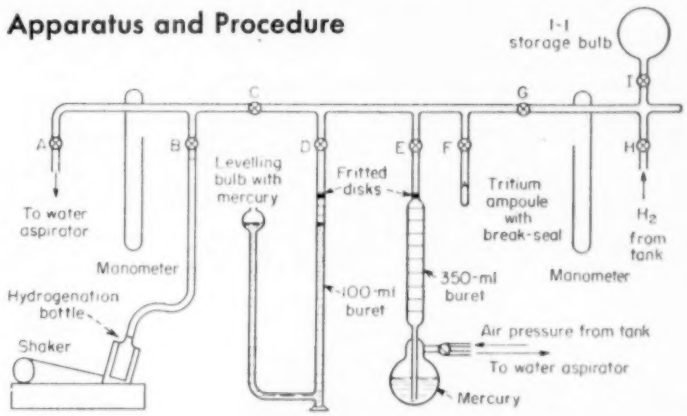
Measurements were taken on the total integrated light output from the tritiated stilbene as a function of its mass by using an RCA 1P21 photomultiplier tube and an electrometer circuit for measuring phototube current. Figure 2 is a graph of relative light output vs mass of powdered tritiated *trans*-stilbene with the cross-sectional area fixed at 1 cm². It should be noted that the powdered stilbene seriously attenuates its own emitted light (*14*) as the mass increases. The slope of the initial portion of the curve is proportional to the relative light output per unit mass, independent of light absorption in the powder.

The measured light output of a radium-activated self-luminescent ZnS-(Ag) phosphor screen‡ of 1 cm² area, which was stated to have a luminous brightness of 12–13 microlamberts at the time of measurement, is plotted for comparison purposes as the horizontal line in Fig. 2. These curves do not indicate the relative visual luminosity as most of the light emitted by the tritiated stilbene is in a region where the human eye is relatively insensitive. However, it is estimated that the apparent brightness of the tritiated stilbene is about 1 microlambert for a sample 30 mg/cm² thick.

Attempts were made to determine the physical light yield of the tritiated stilbene, i.e., the amount of absorbed energy from the tritium beta radiation converted into fluorescent light. The results indicated a conversion efficiency of about 0.6%, which is somewhat smaller than the value of 2 to 3% reported for organic scintillating crystals under bombardment with higher energy electrons (*15*, *16*). Considering

‡ This screen (grade 22M, spec. TT-T-58) was obtained from Radium Chemical Co.

Apparatus and Procedure



for Tritiation of Multiple Bonds

The tritiation apparatus employed is shown above. Capillary tubing is used from stopcocks *A* to *G* to reduce "dead-space."

The hydrogenation bottle containing the catalyst and the material to be tritiated is placed in a mechanical shaker, and the reduction is carried out at room temperature and 1-atmosphere pressure. The entire system with stopcocks *D* and *E* open is evacuated through stopcock *A* with a water aspirator until the solvent boils. With stopcock *G* closed and *H* and *I* open, the 1-liter storage bulb is filled with tank hydrogen to a pressure greater than 1 atmosphere. Stopcock *H* is closed, and the system flushed four times with the hydrogen from the storage bulb, the pressure in the bulb being kept under positive pressure.

After the last flushing, stopcocks *I* and *G* are closed and the rest of the system evacuated. The hydrogenation bottle is left under vacuum by closing stopcock *B*. Then with stopcocks *C* and *D* closed and with the mercury at the top of the 350-ml buret, the tritium ampoule is opened at the break-seal. The mercury in the 350-ml buret is pulled down with the Toepler pump at the base of the buret, in order to transfer the tritium from the ampoule into the buret. Stopcock *E* is then closed and the pressure in the ampoule brought to 1 atmosphere with hydrogen from the storage bulb. The gas in the ampoule is then pulled into the larger buret by lowering the mercury and Toeplered twice back and forth between the buret and ampoule to insure thorough mixing of tritium and protium.

This process is repeated until about 100 ml of gas at 1 atmosphere pressure are contained in the 350-ml buret. The gas is then introduced into the evacuated hydrogenation bottle with the Toepler pump. This direct transfer of the tritium-rich mixture is possible since no pre-reduction of the palladium catalyst is necessary as when platinum oxide catalyst is employed.

The procedure is carried out three times in all, and the pressure in the hydrogenation bottle is brought to 1 atmosphere with hydrogen from the storage bulb. With stopcocks *B*, *D*, and *E* closed, the tritium ampoule is filled to 1 atmosphere pressure with hydrogen from the storage bulb, and then this gas is pulled into the 350-ml buret. Stopcock *F* is closed and *D* opened and the gas forced into the 100-ml buret. With stopcocks *E*, *F*, and *G* closed and *B* open, the pressure in the 100-ml buret is adjusted to 1 atmosphere pressure with the leveling-bulb.

The shaker is then started and the volume of gas used in the reduction measured by means of the 100-ml buret. When necessary, the 100-ml buret is refilled with hydrogen from the storage bulb and the reduction continued. After the theoretical amount of hydrogen has reacted, the shaker is immediately stopped and the apparatus flushed with air to stop further reaction. The apparatus is permanently set up in an efficient hood.

the differences in the methods of computation and the approximations necessary, it is felt that the agreement between our value and that obtained by the more exact method is fairly good.

The relative light output of the tritiated stilbene will be quantitatively checked as a function of time. It is believed that tritiated self-luminescent materials may prove valuable as luminous standards for use in the calibration of phototubes and optical instruments.

Work is in progress on the synthesis of other tritiated self-luminescent materials.

* * *

The advice and technical assistance of Dr. Edward Shapiro, Jennie L. Gaum, Gwynne D. Burkhardt, Richard A. Cotton, and Alexander D. Key is gratefully acknowledged.

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Self-Calibrating Pipette for Remote Colloidal Au^{198} Transfers

By L. E. PREUSS
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Tabern *et al.** describe a pipetting-transferring technique for therapeutic amounts of colloidal Au^{198} in which a slender syringe needle is attached by rubber tubing to a calibrated pipette and inserted into the bacterin bottle containing the colloid. This method requires that each pipette be precalibrated before sterilization to allow for the additional volume due to the needle.

A self-calibrating device is useful in eliminating calibration before sterilization. An ordinary calibrated pipette is attached by means of a transparent plastic needle adapter† to a BD-20, 45 LNR needle. This needle, cut to 3½ in. with the tip squared, will take the plastic adapter taper. The adapter may be shortened at the pipette end.

To use the device following Tabern's technique, the needle and pipette are remotely inserted into the bacterin bottle containing the colloidal Au^{198} and the liquid drawn in so that it fills the needle and the adapter until it just touches the tip of the pipette. When this occurrence is observed through the plastic adapter, by means of a cathotometer or remote viewing mirror, the needle is removed from the liquid and this volume is then drawn up into the pipette where it can be read directly on the pipette calibrations. The volume usually is about 0.05 ml. This whole operation takes place behind the usual lead-brick shielding prior to the first transfer.

The system is advantageous since it allows several pipette-needle combinations to be used without presterilization calibration. Steam sterilization was found to alter the calibrations on the old method. In addition, the adapter is stiff and allows easier manipulation and aiming of the needle in remote pantograph-arm work.

* D. L. Tabern, G. I. Gleason, R. G. Leitner, NUCLEONICS **10**, No. 2, 64 (1952).

† "Venopak," Abbott Laboratories, Inc., North Chicago, Illinois.

A Simplified Liquid-Sample Gieger Counter

By J. U. HIDALGO‡§, S. B. NADLER‡¶, and R. T. NIESET§

A reliable, easily manipulated liquid-sample counter is needed for much of the work with radioisotopes in clinical medicine. In this institution, it is standard policy to do routine radioactivity assays on blood and urine specimens of all patients who have received therapeutic doses of radioisotopes.

A reliable liquid counter has been designed; it is shown in the illustration. Since most of the isotopes used are gamma emitters, a gamma-sensitive tube was selected. The RCL mark 1 model 12 bismuth-cathode tube used in our unit is particularly sensitive to gamma rays of about 0.4 Mev, and

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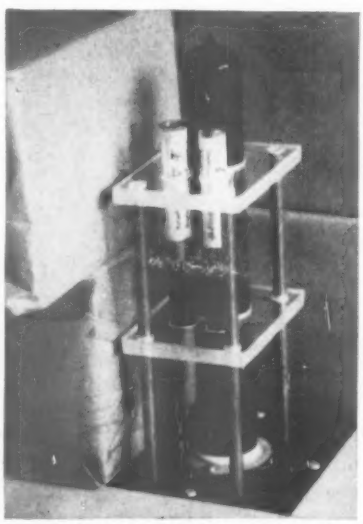

LIQUID-SAMPLE COUNTER with part of shielding removed

is thus suitable for Au^{195} and I^{131} measurements.

The tube is mounted on a small chassis to which a holder for small test tubes is attached. The holder, built of Lucite and brass rods, is designed so that the test tubes are opposite the effective center of the G-M tube.

Since this institution uses the vacuum-tube technic vacutainers for blood sampling, it was deemed more efficient and practical to design the sample holder for this size test tube (8 ml).

The unit is set up to hold one or two tubes, although more tube positions can be provided. Both tube positions are calibrated for tubes containing 1, 2, 3, 4, and 5-ml samples. Each position yields a geometrical counter efficiency of 0.225% for 5-ml samples. For two 5-ml samples counted simultaneously, efficiency is 0.230%.

To express the sensitivity of the counter in concrete terms, a 5-ml sample containing 0.10 microcuries of I^{131} yields a counting rate of 9.88 cps with a background of 1.3 cps.

A check of day-to-day variation of the counter by daily counting of a standard uranium acetate sample shows remarkable stability. A variation of less than 2% was found over a 30-day period.

Vacuum Cleaner for Radioactive Decontamination

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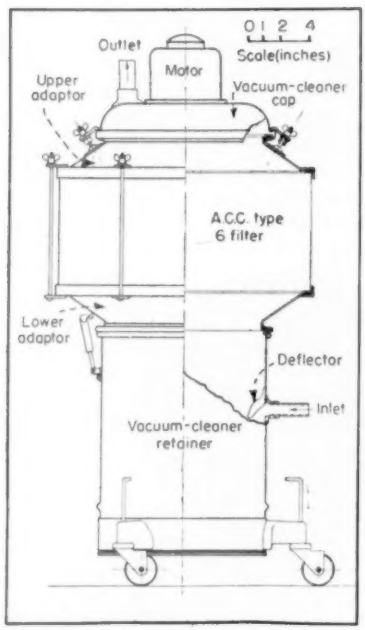
San Francisco, California

Since radioactive contamination from spills can be spread widely in a short time, prompt decontamination is required to protect personnel and to prevent interference with radioactivity measurements. The U. S. Naval Radiological Defense Laboratory uses a modified industrial tank-type vacuum cleaner to clean areas that have been radioactively contaminated by both solid and liquid spills.

The modified cleaner is shown in the illustration. Modification requires an upper and lower adapter, each so constructed that one of its ends fits onto the appropriate cleaner unit and the other onto the face of a high-efficiency filter (such as the Army Chemical Corps type 6 filter). Any commercially available, high-efficiency filter can be used.



MODIFIED tank-type vacuum cleaner

The end of the upper adapter is held in place on the motor-pump unit by special clamps equipped with wing nuts. The lower adapter is attached to the tank unit by the clamps that normally hold the motor-pump unit on the tank. Both adapters are secured to the faces of the filter by several bolts that pass through holes in the periphery of each adapter outside the edges of the filter.

All the modifications required to convert the industrial tank-type cleaner can be made readily in a laboratory machine shop. They do not damage the cleaner, since the filter unit may simply be omitted from the assembly for conventional operation.

Solid or liquid spills are drawn into the tank. Several inches of water in the tank catch the bulk of the spilled material; fine particles are trapped by the high-efficiency filter. The inside of the tank is coated with a strippable film to facilitate its decontamination. It is impractical to consider decontaminating the hose of a cleaner that has been used in cleaning up spills of radioactive material; consequently, it must be disposed of as radioactive waste when excessively active.

The NRDL cleaner can be used as a source of suction and a back-up filter in concentration techniques. In one instance, 40 mg of spilled radium were concentrated in a gas-mask canister that was fastened to the intake of the suction hose. About 35% of the primary spill was recovered in this manner, even though the radium had been widely spread before the clean-up started.

Estimating Exponential Decay

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In radiation control work, an order-of-magnitude estimate of the decay of radioisotopes or of the attenuation of radiation by shielding materials will often suffice. But estimates based on five or more consecutive half-lives or half-thicknesses are almost as much of a chore as calculating the exact solution.

Use of tenth-lives or tenth-thicknesses, however, makes it easy to asso-

ciate specific times or thicknesses with the one-hundredth, one-thousandth, etc., values. Half-lives and half-thicknesses are common values. The conversion to tenth-lives and thicknesses, because of the exponential relation involved, is merely

$$T_{1/10} = 3.322 T_{1/2}$$

or, within 0.3%, $T_{1/10} = 1\frac{1}{3} T_{1/2}$.

In the application of this result, three degrees of accuracy of estimation can be used. The most coarse estimate is made by considering only integral numbers of tenth-lives. For instance, after three such periods, 0.001 of the original activity remains. After five, 0.00001 remains. Within any tenth-life period, interpolation can be made with the first, second, and third half-lives. These give $\frac{1}{2}$, $\frac{1}{4}$, $\frac{1}{8}$, of the activity present at the previous most proximate tenth-life terminus. The highest accuracy by this method is gained by estimating the activity within a half-life period.

Half-Life Example

Consider a bag of laundry contaminated with I^{131}, whose highest spot reading is 50 mr/hr. If this is kept in a storage vault until it reads 0.1 mr/hr, how long must it be stored? (All values in calculation are in days.)

Half-life of I^{131}:	8.0
Tenth-life $1\frac{1}{3} \times 8.0$: (roughly)	27.0
50 to 0.5 mr/hr takes 2 tenth-lives:	54
0.5/4 is 0.125 mr/hr in two half-lives:	16
0.125 to 0.1 mr/hr in about 2 days of the next half-life:	2
TOTAL:	72

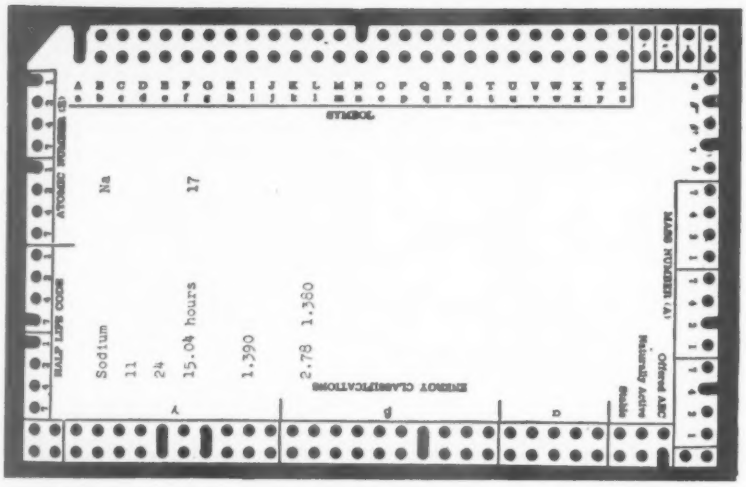
A tabular solution gives 71.74 days.

Half-Thickness

Suppose a large source of Co^{60} is causing a gamma level of 700 mr/hr at a concrete wall rather far from the source. What is the minimum thickness of concrete required to reduce the intensity to 6 mr/hr? (All thicknesses in calculations are in inches.)

Half-thickness (concrete, 1.1, 1.3-Mev gamma):	2.1
Tenth thickness ($1\frac{1}{3} \times 2.1$):	7
700 mr/hr to 7 mr/hr takes 2 tenth-thicknesses:	14
Additional integral half-thicknesses:	0
7 to 6 mr/hr takes about 0.4 in. into the first half-thickness:	0.4
TOTAL:	14.4

A tabular solution gives 14.43 inches.



TYPICAL CARD slotted for classification and selection

Punched-Card Classification of the Nuclides

By J. J. BONINO and K. M. LAING
Pittsburgh Plate Glass Company, Glass Division Research Laboratory
Creighton, Pennsylvania

The most comprehensive and recent lists of the properties of the nuclear species appear to be the National Bureau of Standards compendium "Nuclear Data" (*1*), and the "Trilinear Chart of the Nuclear Species" (*2*). In Britain, Lenihan (*3*) has described a system of presenting some of this information on cards with the edges punched and notched.

We have similarly made use of punched cards, in our case sold by the McBee Company for general classification purposes. Data are coded into the edges of these cards by selectively slotting between the hole and the edge, or between holes of a double row. A predetermined card or a series of cards can be selected from the pack by the use of a long needle which penetrates the aligned holes. When the needle is lifted, the notched cards drop free of the pack.

One set of holes carries the alphabet, so that the symbols of the elements can be coded. Both symbols for elements with two names, such as Ra^{224} and ThX, are used.

The atomic number (Z) and the mass number (A) are coded in a series of "fields," one for each digit, whose holes are labelled 7, 4, 2 and 1. Thus the card for a nuclide with a known A or Z can be searched for and selected from the randomly ordered pack of cards.

The half-lives of radioactive species are divided into 42 classes of limited range. The number of each class is similarly coded into two such fields. Thus all nuclides in a given narrow half-life range may be easily selected. The energies of the various emissions are coded in a somewhat similar, but more direct, way. There was room for coding, in individual holes, whether or not the nuclide was stable, the kind of emission from active isotopes, the availability from the AEC, and the presence of natural radioactivity.

We prepared these cards in triplicate and are able to honor a reasonable number of requests for loan of a set for examination, and, if desired, reproduction.

BIBLIOGRAPHY

1. K. Way *et al.*, "Nuclear Data," circular 499; see also Supplements 1, 2, and 3 (U. S. Government Printing Office, Washington, D. C., 1950–1952)
2. W. Sullivan, "Trilinear Chart of the Nuclear Species" (John Wiley & Sons, Inc., New York, 1949)
3. J. M. A. Lenihan. Isotope catalogue on punched cards, *Brit. J. Applied Physics* **3**, 29 (1952)

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Determination of Film Exposure by Activation of Ag^{109}

By ISADORE B. BERLMAN
Radiological Physics Division
Argonne National Laboratory
Chicago, Illinois

In another article* the new method of determining the amount of reduced silver on exposed and developed film was described. This method involves the activation by neutrons of the silver remaining on the gamma-ray-exposed film after development, and detecting the short-lived (2.3-min) beta activity of Ag^{108} by means of an end-window G-M counter. It was shown that the maximum gamma-ray exposure on du Pont No. 510 film determinable by the neutron activation method was in the vicinity of several hundred roentgens. Considering that the manufacturer recommends the use of this film in the range of 1–35 r, this method provides an appreciable range extension.

* I. B. Berlman, H. L. Lucas, H. May, *Rev. Sci. Instr.* (in press)

The activation method has now been repeated with measurements made on the induced radioactivity of 270-day Ag^{110}. This procedure has some advantages over the other inasmuch as the much longer half-life permits measurements after the decay of activated impurities such as K^{42}, Na^{24}, and S^{35} in the emulsion; moreover, the abundant emission of gamma rays from Ag^{110} also permits measurements with absorbers thick enough to eliminate all beta activity.

The same set of calibrated films that was described in the previous report was activated by a flux of the order of 10^{11} n/cm²/sec for 40 minutes. Each film was activated individually. A NaI(Tl) crystal with a 5819 photomultiplier and a conventional amplifier and scaler were used to detect the resultant gamma-ray activities. The use of lead shielding and proper biasing reduced the background to 0.5 cps. The results are tabulated in the first part of the table. Column one gives the exposure in roentgens, column two the densitometer reading (D_r), column three the counting-rate of a film minus the counting-rate from a blank, column four normalizes the values in column two at 136 r, and column five normalizes the values in column three at 136 r. The counting rate of the blank was 1.3 cps, and the counting time was 1,000 sec.

It must be noted that these readings were the result of one set of films. As in densitometer work there is a variation in the H-D curves from one batch of film to another, so here there is an expected variation from one batch of film to another.

Although the manufacturer recommends the use of this film to the lower range of 1 r, it was of interest to determine how far the linearity could be extended below 1 r. The second part of the table contains analogous results on a second set of films exposed to Ra gamma radiation in the range from 0.4 to 10 r. Columns four and five give the values of the densitometer readings and counting rates, respectively, normalized at 5 r. The counting rate on the blank in this set was 2.7 cps. For better counting rates this set was activated by the same neutron flux for a time longer than the previous set.

The third part of the table lists the results of a third set of film activated by a *nvt* (flux times time) of approximately 5×10^{15} neutrons/cm². At this neutron exposure deterioration has set in and the film has become quite brittle. The counting rate on the blank was 35.6 cps. Columns four and five are the densitometer readings and counting rates, respectively, normalized to 0.8 r.

The useful lower limit seems to be in the region of 0.2 r. This limit is set by the inherent variation from blank to blank. A set of four blanks were exposed independently. The maximum variation was approximately 11%.

In view of the results obtained here, one may conclude that the activation method permits the evaluation of exposure of photographic emulsion du Pont No. 510 within the range 0.3–300 r.

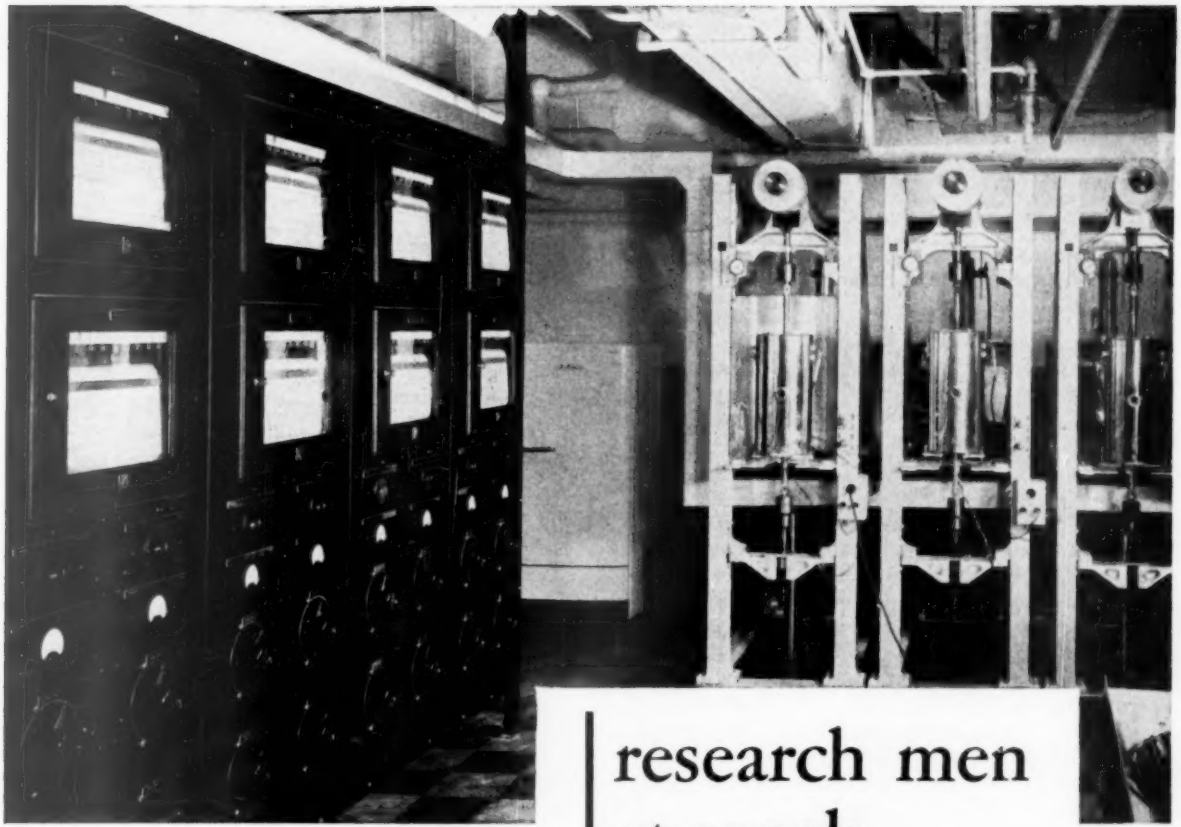
* * *

Thanks are due Mrs. Jean Emer for calibrating and developing the second and third sets of film.

Densitometer Readings Versus Activation Counting Rates

Exposure (r)	*Densitometer reading D_r*	*Activation C_r (cps)*	*Ratio D_r/D_x*	*Ratio C_r/C_x*
First set of films (x = 136)				
10.9	0.75	5.1	0.10	0.11
21.8	1.50	10.3	0.20	0.23
43.7	3.15	19.9	0.42	0.45
86.2	5.10*	32.2	0.68	0.72
136.0	7.5*	44.5	1.00	1.00
214.5	11.8*	63.5	1.57	1.43
545.0	.....	77.2	....	1.74
1,156.0	.....	82.4	....	1.85
Second set of films (x = 5)				
0.4	0.02	0.7	0.08	0.09
0.8	0.03	1.3	0.13	0.16
1.5	0.06	2.3	0.25	0.28
3.0	0.13	4.8	0.54	0.59
5.0	0.24	8.1	1.00	1.00
10.0	0.56	17.3	2.33	2.14
Third set of films (x = 0.8)				
0.05	0	2.4	0	0.11
0.1	0	2.8	0	0.13
0.2	0	5.3	0	0.24
0.4	0.01	10.4	0.3	0.47
0.8	0.03	22.0	1.0	1.0

* Densitometer readings obtained by removing reduced silver on one side of backing.



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BOOKS

The Elements of Nuclear Reactor Theory

By SAMUEL GLASSTONE and MILTON C. EDLUND (D. Van Nostrand Company, Inc. New York, 1952, vii + 416 pages, $4.80). Reviewed by IRVING KAPLAN, Brookhaven National Laboratory, Upton, N. Y.

This book should prove a valuable reference to anyone interested in the theoretical aspects of reactors. The authors have collected an important part of the declassified material now available and have arranged it in a logical and consistent order. The emphasis throughout the book is on the theoretical principles that form the basis for reactor calculations and on the mathematical derivations. The result is a carefully put-together introductory treatise on the mathematical physics of piles, and such a book has been needed for several years.

The virtues just enumerated have been achieved at some cost, namely, at the expense of the physical feeling for what a pile actually is. No real attempt has been made to show how the principles of reactor theory are actually applied in design calculations. The theory of nuclear reactors, as developed here, seems to be divorced from the problems of designing and building a pile. This would not be a valid criticism of the book except for the fact that its authors, as well as the authors of the forewords, have emphasized that the book was inspired by the need to train scientists and engineers in the field of nuclear engineering. I think that the book will be a great help in training theoretical physicists in this field, but I cannot help but feel that it will be less successful in the case of engineers and others not primarily trained in mathematical physics.

Its scope can best be seen running through its contents:

The first four chapters form a brief review of some of the nuclear physics needed in pile theory. The authors treat nuclear structure and stability, nuclear reactions, the production and reactions of neutrons, and the fission process. To one familiar with nuclear physics, these chapters will lump together, in one place, some useful information. The reader to whom the subject of nuclear physics is not familiar will learn the vocabulary and nomenclature that he will need, as well as some of the necessary basic nuclear information.

The fifth chapter deals with the diffusion of neutrons; the emphasis is on monoenergetic neutrons which are, of course, of great importance. The sixth chapter is devoted to the slowing down of neutrons. This subject is treated from a more general viewpoint than that usually met, and the problem of resonance capture is discussed at some length. Chapter seven contains a treatment of the bare homogeneous thermal reactor; the theory of the critical condition, critical size, and the flux distribution in a critical reactor is developed. In the eighth chapter, the theory is extended to the case of the homogeneous reactor with a reflector. The group-diffusion method is introduced and applied to the two-group treatment of the reflector.

Heterogeneous reactors are discussed in the ninth chapter. Formulas are derived for the thermal utilization, the resonance escape probability, and the fast fission factor. In the tenth chapter, the time behavior of a bare thermal reactor is discussed. The reactor period is introduced, the role of delayed neutrons is treated, and formulas are derived for the pile reactivity. The subject of reactor controls is treated in the eleventh chapter. The effects of control rods are worked out on both one-group and two-group theory; the effect of fission-product poisoning is considered, and there is some discussion of the effects of temperature on reactivity.

The last three chapters, twelve, thirteen, and fourteen are devoted to the groundwork of a more advanced and general theoretical development of reactor theory. Among the subjects discussed are infinite slowing-down kernels, the general reactor equation, the critical equation for various slowing-down kernels, group-diffusion slowing-down kernels, convolution of diffusion slowing-down kernels, perturbation theory and its applications, and finally neutron transport theory.

The detailed treatment of the subject matter mentioned is based on the course on Nuclear Reactor Theory given at the Oak Ridge School of Reactor Technology. This approach leads to a degree of coherence and consistency in the way in which the material is developed. There is in existence, however, a large amount of declassified material on reactor theory from other laboratories in the United States, the United Kingdom, and Canada which is not touched upon by Glasstone and Edlund. Although it is obvious that the authors had to make their own selection of material, it could be argued that a considerable amount of valuable material has not been included, nor has its existence been pointed out. Thus, a more extensive bibliography of pile theory would have added to the usefulness of the book.

Finally, the very reasonable price of the book compensates for the inferior quality of the paper and the binding.

Physical Foundations of Radiology

2d ed., by OTTO GLASSER, EDITH H. QUIMBY, LAURISTON S. TAYLOR, and J. L. WEATHERWAX (Paul B. Hoeber, Inc., New York, 1952, ix + 581 pages, $6.50). Reviewed by H. M. Parker, Director, Radiological Sciences Dept., Nucleonics Division, General Electric Company, Hanford Works, Richland, Wash.

The first edition of this book, published in 1944, rapidly became a favorite text among students of radiology and those charged with their teaching. Coinciding as it did with the period in which large numbers of people were introduced to radiation work through the atomic energy programs, it proved to be an invaluable qualitative introduction to radiological physics in that area of activity. The revised edition will permit the text to continue the outstanding service in these fields that its predecessor began.

In format, the new edition is essentially unaltered. The type is unchanged, but there have been increases in line spacing and opacity of the paper, both of which have improved the legibility. Several diagrams repeated from the earlier edition have been acceptably reduced in size. At least in the copy made available to the reviewer, the quality of reproduction of some of the diagrams has unaccountably fallen from the general high standard of the book.

Other figures have been redrawn. In Figures 1–4, the unique rod-shaped neutrons of the 1944 edition are here replaced by conventional spherical neutrons. One can only speculate as to the number of peculiar responses to examination questions that led the authors to make such changes. What

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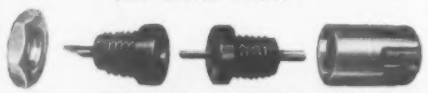

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TERMINALS: *Solder Type* (Bifurcated or Turret) brass, hot tin dipped; *Screw Thread Type* (Tapped insert or Threaded stud) No. 4-40 or No. 6-32, brass, cadmium plated, clear iridite finish.

MOUNTING METHOD: *Rivet*, hollow aluminum shank (.094" O.D.) assembled by swaging or spinning; *Tapped Insert*, brass, cadmium plated, clear iridite finish, assembled with No. 4-40 or No. 6-32 standard machine screw; *Threaded Stud*, brass, cadmium plated, clear iridite finish, assembled with No. 4-40 or No. 6-32 nut.

BREAKDOWN VOLTAGE:

Stand-off Body Length	D.C. Voltage
7/32"	7,000 V
3/8"	14,000 V
17/32"	22,000 V
19/32"	24,000 V
Feed-through Creepage Length	
5/32"	4,500 V
9/32"	8,000 V

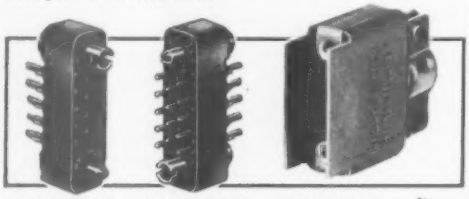

Photo and Drawing of SMRE-14 actual size. Other sizes determined by number of contacts.

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SM1S	SM1P	1	.043	.02	.04	.02	....	5400	...	1750
SM2S	SM2P	2	.0225	.02	.02	.02	1600	2600	800	1100
SMRE 7S-G	SMRE 7P-G	7	.0225	.1	.1	.1	2450	2050	950	675
SMRE 14S-G	SMRE 14P-G	14	.0225	.1	.2	.1	2450	2050	950	675
SMRE 20S-G	SMRE 20P-G	20	.0225	.2	.2	.2	2450	2050	950	675
SMRE 26S-G	SMRE 26P-G	26	.0225	.2	.2	.2	2450	2050	950	675
SMRE 29S-G	SMRE 29P-G	29	.0225	.2	.2	.2	2450	2050	950	675
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is more surprising is the failure to correct such obvious errors in the same figures as writing HE for helium and CU for copper.

Revisions and Additions

The text revisions include minor revisions to almost all chapters, complete rewriting of some chapters, and addition of new chapters.

The minor revisions are well conceived. Some inclusions, such as the elaboration of elementary electrostatics, come from the authors' appreciation of the students' difficulties. Some omissions, such as the previous account of pre-Coolidge roentgen-ray tubes, relieve the text of obsolete material. Most striking of the minor changes is an attempted new explanation of the production of X-rays, which rather courageously amounts to an admission that a satisfactory elementary picture of this basic part of the physical foundations of radiology cannot be given!

Less satisfactory in some respects are the completely rewritten chapters. While the general excellence of the book stems from the collaboration of four authors outstanding in the field, there are areas in which a possible lack of unified approach results. To this reviewer, at least, it would seem more appropriate to attack basic dosimetry of roentgen rays and gamma rays as a single topic. When one deals with dosimetry of photonic radiation, it is purely an accident of birth as to whether the photon should be labeled "roentgen ray" or "gamma ray." The Bragg-Gray principle can be used as such a base provided that the theoretical limitations on minimum depth of cavity in the solid medium (which becomes minimum wall thickness of the derived chamber), and on size of cavity (which becomes the internal dimension of the chamber) are stipulated. These severe limitations to direct practical application are omitted from the text. The great advantages of using a chamber wall identical in atomic composition with the chamber gas, to remove the second limitation, are then less obvious to the student. The fundamental separation of dosimetry at this point into (a) radiobiological dosimetry, using tissue-wall chambers, and (b) "roentgen" dosimetry, using air-wall chambers, including the free-air chambers, is somewhat obscured from the student.

The revised chapter on protection in radiology has been expanded sub-

stantially in recognition of the extensive work in this field since the date of the first edition.

The three chapters described as new are in some respects quite disappointing. That dealing with supervoltage generators, high-energy accelerators, and nuclear reactors, derives half its material from the earlier edition. Added are good accounts of the synchrocyclotron, betatron, linear accelerator, and synchrotron. The description of the nuclear reactor is less satisfactory. This small section contains several errors, in sharp contrast with the text as a whole. It is doubtful whether the student will obtain a sound picture of the basic elements of the initiation and control of the nuclear reaction. It is also surprising that the types of nuclear reactor that may soon become as common in our universities as the cyclotron now is are not even mentioned.

Another new chapter is concerned with the measurement of radiations from radioisotopes. This provides an adequate introduction to the field. One could quibble about the balance of the presentation, particularly in such points as the omission of specialized equipment for the assay of liquid or gaseous samples, and the rather unkind manner in which scintillation counters are mentioned, only to be followed by a barrage of objections. The authors have wisely included a section on statistical fluctuation; whether this should have had as much space as the description of the Geiger counter itself is questionable. It is perhaps justified by the proposition that the understanding of an instrument requires its actual use by the student, whereas statistics can be appreciated fully in the text.

The remaining new chapter relates to dose considerations for isotopes in the body. While the appropriate subject matter is covered, it is, to this reviewer, done in a singularly clumsy manner. To read that the dose per minute is given by $2.54\bar{E}_\beta$ er per hr per μc per gm leads to low reader perception in comparison with a simple general formula, dose-rate $= 61(E \times Q)/W$ rep per day, where E has the same meaning as $\bar{E}_\beta$, Q is the activity in μc, and W is the mass of tissue in which the active material is distributed. This is the old "61 Formula," which for the past few years has been obsolete and replaced by the "55 Formula," reflecting the essentially universal agreement to accept some kind of

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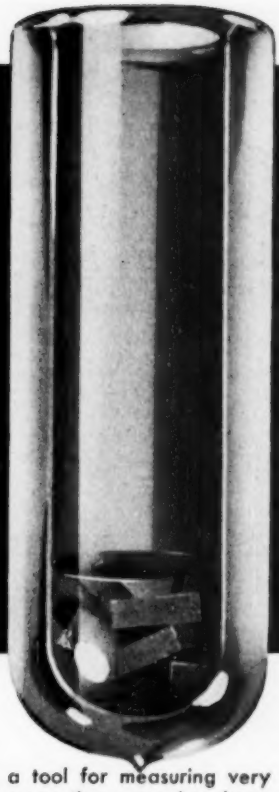
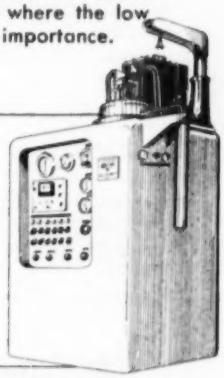
100 pounds of
lead 0.1°K
in one minute



The use of liquid helium as a tool for measuring very small heat influxes, suggested some time ago, has been reported on recently. By the use of a constant temperature calorimeter containing liquid helium, power levels of the order of a few microwatts can be measured. This is possible because of the almost zero values of specific heats near 4° K and the small latent heat of vaporization of liquid helium. Such a calorimeter has been used for the measurement of the total emissive energy of a β ray source, and it should also be of use in measuring low energy γ rays. A substantial amount of lead could be used at 4° K for absorption purposes, with little contribution to the heat capacity of the measuring system.

Directional effects in radioactive emission near .01° K have recently been reported from Oxford and Leiden as a result of the first successful experiments on nuclear alignment. Various similar experiments have been proposed, and, undoubtedly, in the near future, physicists will make much more use of temperatures near 0° K where the low energies of nuclear interactions become of importance.



The ADL Collins Helium Cryostat made by Arthur D. Little, Inc. is the basic tool in low temperature research. It liquefies helium and maintains a test chamber from normal room temperature to within two degrees of Absolute Zero. By using the adiabatic demagnetization process, the temperature can be further reduced as low as 0.0015°K.

Write for Bulletin N24-2

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TABLE OF CONTENTS

1. Fundamental concepts of neutron physics
2. The pile as a neutron source
3. Neutron standardization
4. Fast neutron research
5. Resonance neutrons in pile
6. Resonance neutron beams
7. Thermal neutrons inside the pile
8. Neutron diffusion measurements
9. Thermal neutron beams
10. Neutron diffraction
11. Neutron refraction, reflection, and polarization.
12. Health physics

Appendixes

1. Constants, formulas, and conversion factors
2. Atomic mass values
3. Low-energy neutron cross sections
4. Experimental course in pile physics

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roentgen equivalent based on 93 ergs per gram, rather than the earlier 83 ergs per gram.

This raises a serious objection to the subject chapter. An earlier chapter accepted the rep as a convenient notation. Here the rep and "equivalent roentgen" (er) are said to mean essentially the same thing (both tied to 93 ergs per gram). Then "er" is used throughout, and used erroneously on the basis of 83 ergs per gram. The best interests of the student would have been served by the selection of the more widely accepted notation. (Also, it would help the student to explain the physics behind the 83 and 93 numbers.) Further liberties have been taken with units in the examples on page 395. Here the beta-ray component of dose is computed in "er," and the gamma-ray component in roentgens; the combined dose is then given in roentgens. This is unacceptable, and potentially confusing to the neophyte, who must now wonder why the "equivalent roentgen" was introduced at all. This is a fair question that could well have been answered in another part of the text.

If the "55 Formula" had been used, simple extensions could have been given to cover the cases in which a uniform daily dose is administered, or the total dose from a single administration is integrated over a given time, or a biological half-life is to be considered. The safe tracer dose calculation is just one application of such formulas. It could have been more elegantly presented as such (and, incidentally, without resorting to the "microcuries destroyed" concept).

The section on personnel safety considerations appears out of place in this chapter. The data are given in proper place in the protection chapter. Moreover, they are restricted to that phase of isotope protection that is best understood by those familiar with handling sealed radium sources. By inference, the more novel phases which involve defense against possible ingestion, inhalation, or percutaneous transmission are minimized.

It is the nature of a review of this type that considerably more space goes into criticism than approval. It must be emphasized, therefore, that the proper perspective is given by the following summary:

The text is an excellent one for its intended function as a "compact, elementary and nonmathematical guide to radiation physics for the physician

and the student." This reviewer believes that a more unified approach to the fundamentals of dosimetry would have increased its value; he is relatively disappointed with the three new chapters, and particularly so with the presentation of dose considerations for internal emitters. However, the authors are universally recognized as the distinguished core of teachers in this field. One can confidently assume that the particular teaching methods presented have been well tested and shown to lead to adequate understanding for the intended audience.

BOOKS RECEIVED

Meson Physics, by Robert E. Marshak, McGraw-Hill Book Company, Inc., New York, 1952, viii + 378 pages, $7.50. *(To be reviewed.)*

Methods of Statistical Analysis (2d edition), by Cyril H. Goulden, John Wiley & Sons, Inc., New York, 1952 vi + 467 pages, $7.50.

A complete revision of the 1939 edition, with some new material added —for the research worker interested in experimental design and analysis. Examples are worked out with the necessary algebra to illustrate theory.

ALSO OF NOTE

Radioisotope Techniques—Vol. II, Industrial and Allied Research Applications, published by the British Ministry of Supply. This 177-page pamphlet contains the proceedings of the Isotope Techniques Conference held at Oxford, July, 1951, and sponsored by the Atomic Energy Research Establishment at Harwell, England. It is profusely illustrated and touches on general, metallurgical, and chemical applications, gamma radiography, counting techniques, ion exchange, nondestructive testing, static elimination, and radioactivation analysis. *British Information Services, 30 Rockefeller Plaza, New York 20, N. Y., $5.75.*

Availability of USAEC Research and Development Reports. This is TID-4550 (Revision No. 1, November, 1952), a 20-page summary of ways to locate and/or obtain copies or abstracts of the several thousand reports issued by the Atomic Energy Commission and its contractors. *Technical Information Service, Atomic Energy Commission, P. O. Box 62, Oak Ridge, Tenn.*

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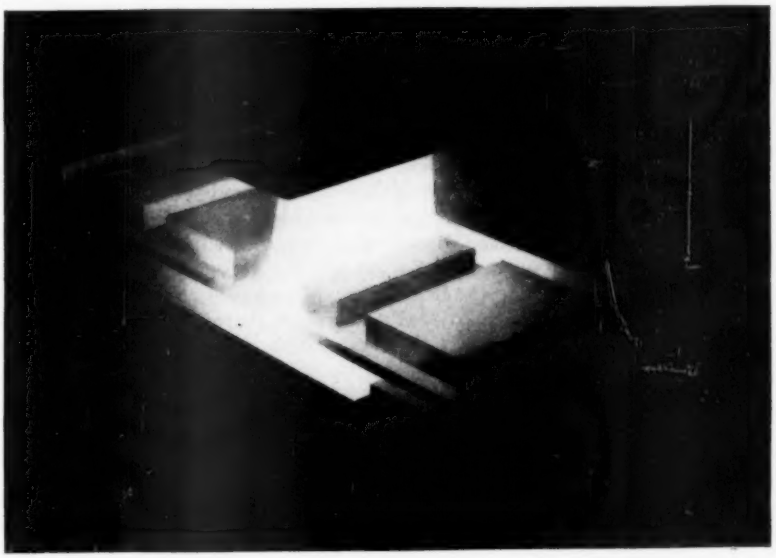

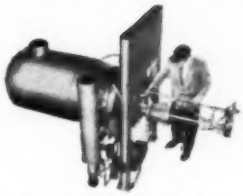

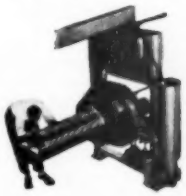

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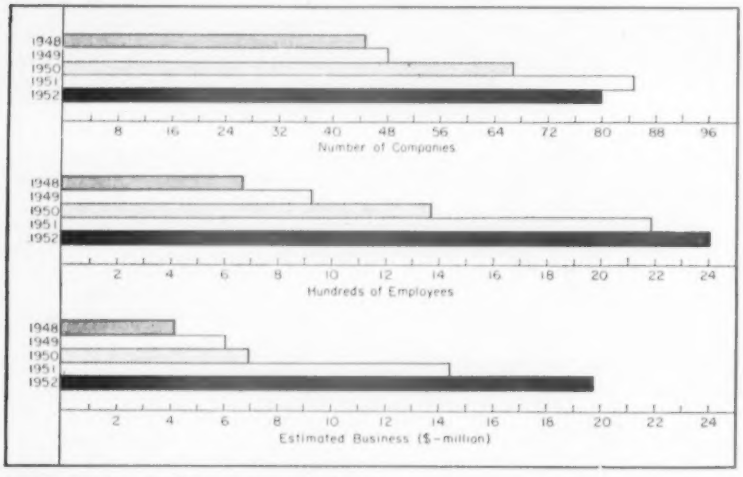
NUCLEONIC EVENTS

Radiation Instrument Industry Does $20-million Business in 1952; AEC and Military are Principal Customers

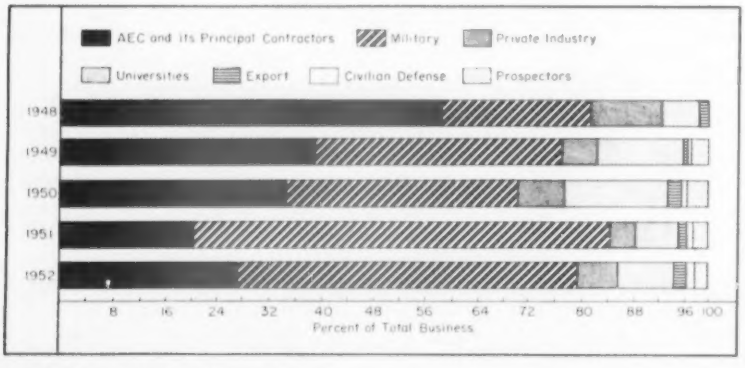
The radiation instrument industry, virtually nonexistent in 1946, had a volume of business of almost $20-million and employed 2,400 persons in 1952, according to a survey conducted by the Atomic Energy Commission. The two charts below show the growth of the industry during the last five years and a breakdown on the market for the output of the industry during that time.

The two largest customers for radiation instruments have been the military and the AEC and its principal contractors. In 1948, AEC accounted for 58.7% of the business and the military for 22.5%. Five years later, in 1952, the situation was almost completely reversed, with AEC accounting for 27.4% and the military for 52.5%. The remainder of the market is accounted for by private industry, universities, civilian defense, export, and uranium ore prospecting.

The survey covers more than 90% of the radiation instrument industry in terms of business volume. Seven companies with probable business volume in excess of $1-million each in 1952 account for about 50% of the industry's activity. About one-quarter of the companies accounted for less than $100,000 worth of the 1952 business, and another one-quarter accounted for $100,000–200,000 of the 1952 business.



GROWTH of the radiation instrument industry



MARKET for radiation instruments

Hanford to Get New Chemical Processing Plant

As part of the current Atomic Energy Commission plant expansion authorized by the 82nd Congress, a large chemical processing plant will be built at the Hanford Works, Richland, Wash.

The plant, which will supplement present chemical processing facilities, will be needed to handle an increased production of plutonium. Primary purpose of the plant will be for Hanford operations.

A $40-million construction contract for the facility has been awarded to Blaw-Knox Co., Chemical Plants Division, Pittsburgh, Pa. Hiring of construction workers is expected to start in April, and the construction work will cover a period of about two years.

Basic design and engineering will be done by General Electric Co., and architect-engineer services are to be provided by Vitro Corp. of America.

AEC Wants $2.7 Billion for Fiscal 1954

The federal budget for fiscal 1954 which President Truman presented to Congress last month calls for expenditures of $2.7-billion by the Atomic Energy Commission for the year. For fiscal 1953, estimated expenditures are $2-billion, and actual expenditures for fiscal 1952 were $1.67-billion.

The budget lists $1.9-billion for new facilities which were authorized in the supplementary appropriations bill of 1952 (NU, Aug. '52, p. 74). This includes about $400-million appropriated in 1952 but which has to be rerequested. Some of the $1.9-billion is included in the $2.7-billion figure, that which is not must be expended within four years of approval.

No detailed breakdown on the way these funds are to be spent will be available until the complete budget is formally presented to Congress for its consideration.

In the message to Congress in which he gave these over-all budget figures,

President Truman said that the budget provides for continuing research in the development of reactors for the production of electric power. He also said that funds will be provided for continuance of research in medicine, physics, chemistry, and biology.

AEC Expands "Information for Industry" Program

Plans for expediting the reporting of nonsecret industrial developments in the nation's atomic energy plants and laboratories have been developed by the Atomic Energy Commission. Instructions issued by AEC General Manager Marion Boyer to the operations offices of AEC call for the principal initiative for the dissemination of industrial information to be placed on the operating contractors.

Special effort is to be applied by contractors to uncover and arrange for publication of unclassified techniques useful to industry. AEC's objectives in this program are:

1. To create on the part of industrial management and technical personnel constructive interest in the atomic energy program, its achievements, problems, and objectives.

2. To facilitate the development of industrial competence in specialized atomic energy techniques.

3. To develop the maximum contribution of atomic energy technology to the nation's technology.

In this first definition of AEC policy on the dissemination of industrial information, the initiative is being placed in the hands of the contractors because the bulk of the information involved originates in work carried out by the contractors. The degree to which AEC will aid contractors to cover the costs of this new program has not been worked out in detail but will be taken up when new or modified contracts are entered into.

It has long been realized that scientific information developed by AEC personnel and contractors found natural outlet through the journals of the scientific societies and elsewhere, but that other kinds of technical data—techniques and general "know-how"—were not getting into the literature. In the first place, nonscientist personnel do not have the same incentives for preparing technical papers for publication; and secondly, the security problem makes it virtually impossible

The Editors Hear . . .

• There is only one known plutonium reactor operating in the world—at Los Alamos. However, with the prospect of more Pu-producing reactors coming into existence, more attention is being paid to designing reactors that can use Pu as fuel.

• AEC does not expect to spend large sums of money on civilian nuclear power in fiscal 1954. The AEC reactor division wanted $60-million for such work, but AEC commissioners vetoed the idea.

• From interviews with Gordon Dean, AEC chairman, W. Sterling Cole, ranking Republican Congressman on the Joint Congressional Committee for Atomic Energy, and Bourke B. Hickenlooper, ranking Republican Senator on the Joint Committee, NUCLEONICS learned that:

→Clear proposals indicating that industry has a desire to invest its own money in nuclear power development will be very well received. Such proposals would undoubtedly result in hearings to determine how industrial investment could be protected by revision of the Atomic Energy Act.

→Lacking such a show of positive interest on the part of industry, considerations of revisions of the Act will move much more slowly. In fact, if the government is to foot the bill, Cole sees no reason why the Act should be changed now.

→Hickenlooper feels that hearings should be held immediately to get all opinions on the record.

→Government financial support of industrial proposals for nuclear power development hinges on two basic points: (1) Should nuclear power development be pressed? and (2) Does the U. S. need more Pu than presently contracted for facilities will produce? It appears to be quite questionable whether we need more Pu, according to Cole. From published expenditures, this country has been concentrating on production of U^{235}, and the cost per gram of U^{235} is probably less than a tenth that of Pu.

→Dean still feels that there should be major declassification of power reactor data. In addition to speeding progress in reactor technology in this country, such action would help our relations with our foreign suppliers of uranium. Some of our suppliers are power hungry, and if power reactor data were declassified, we could assist these countries with technical information.

→With such a declassification (and a revision of the Act), it might then be possible for industrial organizations in this country to build economically competitive reactor power plants in foreign countries where power costs are high.

→Both Cole and Hickenlooper favor major reactor data declassification. Hickenlooper feels AEC has the authority right now for declassifying much more that it has. He feels it is not wise to give selected companies access to secret data. Rather it is better to open things up more.

→Cole believes that if private industry won't pay for reactor power development, then government should. Hickenlooper says AEC should stay out of civilian nuclear power and that industry should be given every encouragement.

• The 5th tripartite declassification conference will be held in Chalk River in April. One of the important questions to be considered is how much more information on reactors can be given out to satisfy industrial interests. Of particular interest now are factors that bear on the economics of power reactors.

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for the technical press to pursue its customary role in locating and evaluating potentially publishable material.

The program calls for active efforts on the part of contractors in locating techniques useful to industry by encouraging personnel to include in manuscripts material which they think could be declassified, and by "regular survey and evaluation from the viewpoint of industrial interest" of various areas of classified technology.

Advisory Committee

The "Information for Industry" program began shortly after December 1948 when an industrial advisory group, which had reviewed with the AEC its relations with industry, recommended that much more industrial information be declassified and made available to American industry. To aid and advise the AEC on techniques for carrying out this recommendation, an *ad hoc* committee of men representing the professional engineering societies and the technical press was organized; these men were chosen for their knowledge of industrial practices. This advisory group examined AEC documents, surveyed technical practices in certain contractors' laboratories and plants, and made recommendations to the AEC.

The new program for encouraging and aiding contractors to dig out and to disseminate, by all known methods, nonscientific (but technical) techniques useful to modern industry is a result of this association between AEC and trained and experienced editors of technical journals.

The advisory committee has now been made a permanent body with the title of "Advisory Committee on Industrial Information."

Program for Speeding Private Nuclear Power Proposed; Calls for McMahon Act Revision and Federal Pu Purchase

Manson Benedict, professor of nuclear engineering at the Massachusetts Institute of Technology, has proposed a specific five-step program to speed the development of industrial nuclear power. According to Benedict, cost-minded private companies should be encouraged to enter the nuclear power field to drive down expenses, and these companies should be provided with incentives such as ownership of patents, reactors, and possibly natural uranium.

Benedict claims that there are four factors which are causing the delay in the development of industrial nuclear power. They are: technical difficulty, lack of immediate demand, security, and the Atomic Energy Act.

The specific proposals, which were made in anticipation of debate in Congress on revision of the Atomic Energy Act, are:

1. The government and industry should build a limited number of dual-purpose reactors. So that practical experience with a nuclear power plant can be gained, the government should take the risk that the premium value of plutonium for military purposes may be of limited duration.

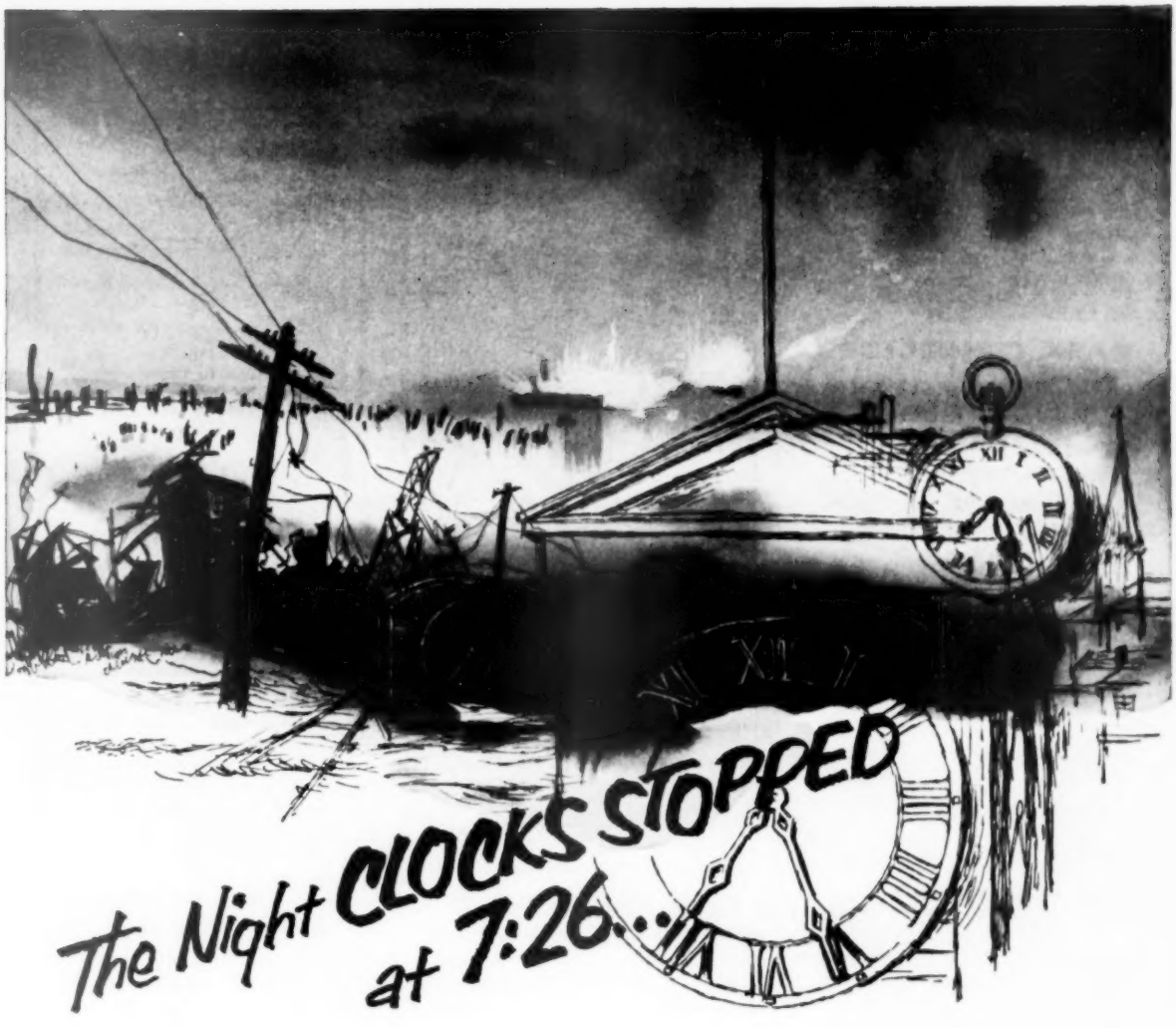
2. Private companies should be encouraged to enter the nuclear power field to learn how to reduce the cost of nuclear power plants and advance the day when breeding will be economic. Revision of the Act to permit private companies to own nuclear power patents would be a valuable incentive.

3. There should be no relaxation of security solely to facilitate development of industrial nuclear power. The time is not ripe for widespread declassification of technical information on atomic energy. We may be able to declassify basic data which we have reason to believe are known to others, but we should not declassify information on plants and processes, even though this would advance development of private nuclear power.

4. Within the existing security framework, dissemination of information should be facilitated. The Atomic Energy Commission's policy of clearing representatives of many companies and institutions, and inviting them to work in the atomic energy field, should be expanded even further.

5. With fissionable material so vital to the security of the United States, it would be premature to amend the Act to permit others besides the government to own U^{235} or Pu. However, some liberalization of the provisions of the Act should be possible. Private companies should be allowed to own reactors, and to use fissionable material under government license. Outright private ownership of natural uranium should be considered in view of its lower strategic value.

Several companies have expressed



Some 9,500 people were in South Amboy, N.J., that drizzly evening in 1950. At the waterfront, longshoremen were transferring the last of 12 freight cars of ammunition to lighters that would carry it to a waiting vessel in Raritan Bay.

But the City Hall clock never got to 7:27—and the freighter's deadly cargo never got loaded. Explosions shattered windows over a radius of 12 miles; and hundreds of people looked at their arms and legs and saw that flying daggers of glass had stabbed them.

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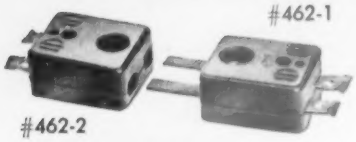

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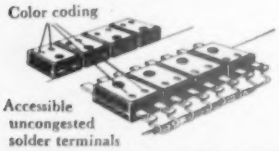

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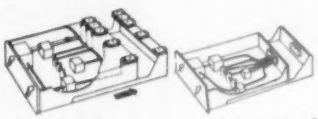

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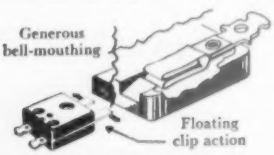

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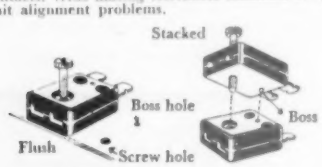

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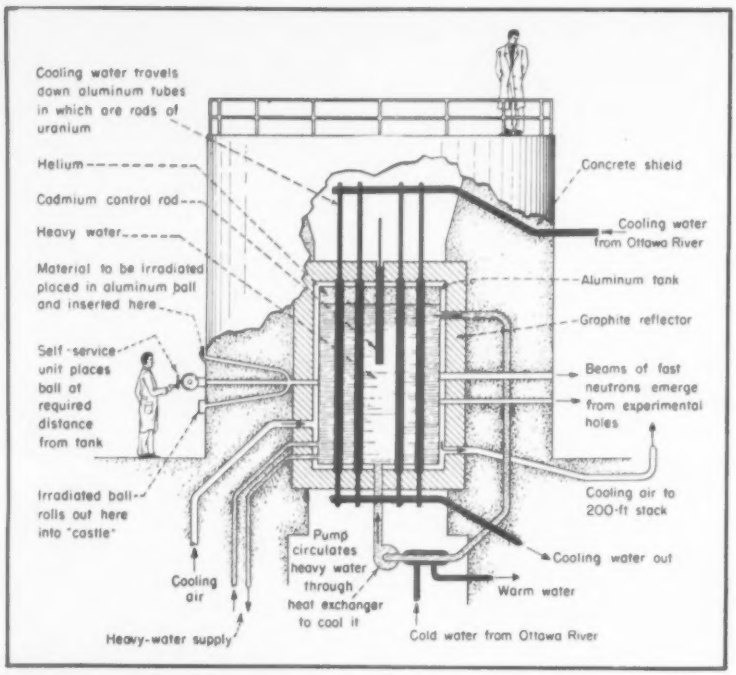
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Cadmium control rod
Heavy water
Material to be irradiated placed in aluminum ball and inserted here
Self-service unit places ball at required distance from tank
Irradiated ball rolls out here into "castle"
Concrete shield
Cooling water from Ottawa River
Aluminum tank
Graphite reflector
Beams of fast neutrons emerge from experimental holes
Cooling air to 200-ft stack
Cooling water out
Warm water
Pump circulates heavy water through heat exchanger to cool it
Cooling air
Heavy-water supply
Cold water from Ottawa River

NRX REACTOR AT CHALK RIVER, CANADA, has 176 water-cooled aluminum tubes containing rods of natural uranium which are surrounded by a heavy water reflector contained in aluminum tank. Dismantling and examination following a breakdown in December is expected to take quite a few months. The shell of NRU, another heavy-water reactor, is going up near NRX. Among the new features for NRU are an improved mechanism for automatic control, and an arrangement for easier removal and replacement of uranium rods

interest in owning a natural uranium reactor that produces power and a mixture of uranium and plutonium, which might be sold to the government for final processing. According to Benedict, it is hard to see how such an arrangement would endanger the national security, and it would certainly make nuclear power a more attractive field for private companies.

Benedict pointed out the paradox that although military demand for Pu would permit production of nuclear power at a profit, the demand is so acute that there has not been time to learn how to produce nuclear power dependably. Our reactor developments have aimed, he said, at producing Pu or power for military production, and there is no project aimed directly at the eventual production of industrial nuclear power at costs competitive with other fuels.

AEC Opens Some Hanford Land; Warns of Danger

The Atomic Energy Commission has announced that it will release from restriction about 87,000 acres at the extreme east and west ends of the Wahluke Slope across the Columbia River from its Hanford production plant. The announcement was accompanied by a warning that the action does not mean that all risk to life and property in the released lands has been eliminated.

A statement signed by the four AEC commissioners said that the only real danger in the area (other than enemy action) is the unlikely eventuality that one of the reactors would go completely out of control. There is said to be no risk in the area resulting from normal operation of the Hanford plant.

No towns or cities will be permitted to be established within 25 miles of the Hanford reactor area. (Hanford reactors are unique in design and construction, the announcement said. Potential hazards at other AEC reactor locations are not so great.)

If one of the reactors should go completely out of control, dangerous amounts of radioactivity could be released to the atmosphere. The reactors cannot explode, but, under the worst possible conditions, they could produce so much heat that the fuel

elements would melt and release a very dense cloud with a high gamma-ray activity. This would be more dangerous than a cloud produced by an atomic bomb explosion.

Studies on the development of improved safety features are continuing, and if the risk inherent in the Hanford operations is further reduced, release of more lands, closer to the reactors, will be considered.

A method will be established for warning Wahluke Slope residents in the event of disaster. Development of an evacuation plan for families in the area will be encouraged and assisted by the Hanford Operations Office.

IRE Convention to Include Papers on Nucleonics

Two of the technical sessions of the 1953 national convention of the Institute of Radio Engineers, to be held in New York City, March 23–26, will contain papers of interest to people in the nucleonics field.

The session devoted to nucleonics will be held in the morning of March 26 and will be devoted to the following papers: *Servomechanism for Remote Manipulation*, Raymond C. Goertz, Argonne National Laboratory; *The Applications of Secondary Emission Multipliers to Nuclear Particle Measurements*, George Morton, RCA; *Billion-electron-volt Accelerators*, Kenneth Green, Brookhaven National Laboratory; *Instrumentation Developments in Fast Neutron Dosimetry*, G. S. Hurst, R. H. Ritchie, Oak Ridge National Laboratory; and *Electronic Circuitry for Nuclear Reactors*.

A session on medical electronics, to be held in the morning of March 26, will contain the papers: *Concerning the Use of High-Energy Particles and Quanta in the Determination of the Structure of Living Organisms*, R. J. Moon, University of Chicago, and *Possible Medical and Industrial Application of Linear Electron Accelerators*, W. C. Barber, Stanford University.

IN BRIEF

• **Atomic hazard survey.** The California department of public health wants $18,000 in its 1953–54 budget for a survey of atomic hazards in California industries resulting from increasing use of radioactive materials and X-rays.

• **Hot cell.** A hot cell and building will be built for use in the Materials

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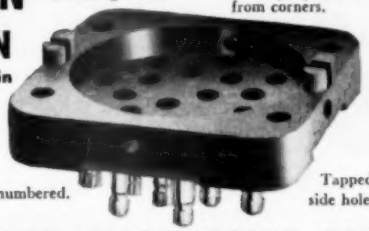
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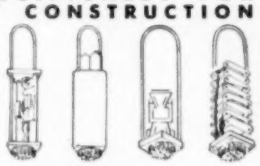

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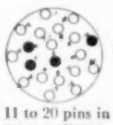

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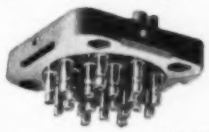

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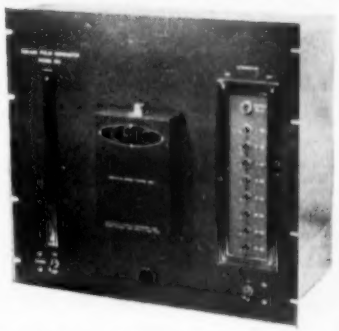

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Testing Reactor area at the Reactor Testing Station, Arco, Idaho. The cell will permit visual examination, modification, adjustment, and repair of experimental equipment after irradiation in the reactor, as well as testing of physical and mechanical properties of irradiated materials.

• **Material wear.** The Michigan-Memorial Phoenix Project has received $250,000 from the Chrysler Corp. for a study of the use of radioactive tracers in the wear of various materials, as well as the use of radioisotopes in determining the atomic structure of materials.

• **Dutch power reactor.** Leading nuclear scientists in Holland have made an urgent appeal to industry to place experts and capital at their disposal for the purpose of building a power reactor in Holland. It is said that within 25 years, Dutch sources of coal will be near exhaustion.

• **Waste disposal.** The health-safety and waste-disposal methods at the Knolls Atomic Power Laboratory, Schenectady, have been approved by the Mohawk River Advisory Committee. The committee reported that the controls appeared adequate to assure conformance with anti-pollution standards of New York.

NUCLEAR NEWSMAKERS

Brian Flowers, one of the senior scientific officers at Harwell, will fill the post of chief theoretical physicist which has been vacant since the arrest of Klaus Fuchs in 1950.

James H. McMillen is now on the physics staff of the division of mathematical, physical, and engineering sciences of the National Science Foundation. He formerly was chief of the hyperballistics division of the Naval Ordnance Laboratory.

Charles A. Thomas, president of Monsanto Chemical Co., will receive the 1953 Perkin Medal of the American section of the Society of the Chemical Industry.

J. R. Townsend has joined Sandia Corp. at Albuquerque, N. M., as director of materials and standards engineering. He is on leave from Bell Telephone Laboratories, where he was director of materials applications engineering.

Thomas Lauritsen, associate professor of physics at California Institute of Technology, is in Denmark lecturing and doing research in experimental physics at Niels Bohr's Institute for

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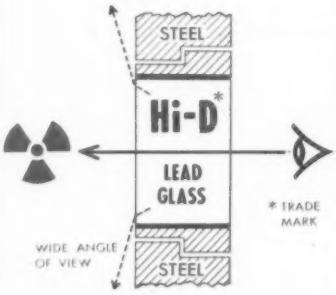

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LETTERS

"mc" and "μc"

DEAR SIR:

The accepted abbreviation for milligram is "mg." The accepted abbreviation for microgram is "μg." In an analogous manner should not "mc" be the abbreviation for millicurie, and "μc" be the abbreviation for microcurie? Of course they should—and yet there continue to appear papers in which "mc" is used to mean microcurie. Usually it is quite apparent which is meant, milli or micro, when the abbreviation is used. Occasionally, however, confusion may, and does, arise. I should like to enter a plea that authors either spell out the words or that the standard abbreviations be used and that editors of journals involved keep an "eagle eye" out for situations in which there may be confusion, and act accordingly.

HENRY LANZ
Associate Director, Radioisotope Unit
Veterans Administration Hospital
Dallas, Texas

(*NUCLEONICS is in accord with this reader's comment and regularly follows the practice recommended.*—Editor)

Theoretical Physics at the University of Copenhagen. The trip and lectureship are being made under an exchange grant awarded under the Fulbright Act.

J. M. Smith, Jr., has been appointed manager of radiological engineering at the Hanford Works, Richland, Wash. He is succeeded by **D. P. Ebright** as head of the radiological standards unit.

Harold C. Urey has been appointed Martin A. Ryerson distinguished service professor of chemistry at the University of Chicago.

O. Kenton Neville, who was a senior scientist in the chemistry division of the Oak Ridge National Laboratory, is now director of the chemistry department of the Nuclear Instrument and Chemical Corp., Chicago.

Paul E. Klopsteg, assistant director for mathematical, physical, and engineering sciences of the National Science Foundation, has been appointed to the new position of associate director of the Foundation.

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New AEC Patent Releases

The following patents, released by the Atomic Energy Commission, are available for royalty-free, nonexclusive licensing. Applicants should apply to the Chief, Patent Branch, Office of the Counsel, U. S. Atomic Energy Commission, Washington 25, D. C. Identify patents by number and title.

Selective Electrodeposition of Silver (2,612,470) J. C. Griess, Jr., L. B. Rogers—method for selectively recovering silver from an alkaline aqueous solution containing trace amounts of silver, macro quantities of palladium and a complex-forming substance.

Compensated Thermocouple (2,612,779) S. F. Mulford—as a balanced-resistance-bridge-type setup, thermocouple measures temperature of a current-carrying conductor.

Mega Voltmeter (2,613,235) C. E. Grunsky—a new circuit for a vacuum-tube voltmeter capable of accurately measuring the peak voltage of pulses having extremely short duration.

Voltage Measuring Apparatus (2,613,236) H. Palevsky, R. K. Swank—an ultrasensitive electrometer system for measurement of electrostatic charges and of small d-c voltages from high-impedance sources.

Welding Device (2,613,305) R. W. Clack—device for welding in an evacuated space by electron discharge between the parts to be welded.

Dosimeter (2,613,327) A. O. Beckman, H. H. Herd, A. D. Robinson—pocket-size, electroscope-type radiation dosimeter has lens arrangement for reading, hermetically sealed and separate ionization and electroscope chambers, and a simplified charging means.

High-Voltage Regulator (2,613,344) W. H. Nelson—simplified high-voltage regulator has a series-connected lesser tube controlled by a negative feedback amplifier having a minimum phase shift around the regulator loop.

Diffusion-Measuring Meter (2,613,531) C. G. Bacon—by measuring rate of gas diffusion with ion gages, apparatus determines porosity.

Uranium Purification as Complexes of Esters of Trifluoroacetoacetic Acid (2,614,113) H. I. Schlesinger, H. C. Brown—method for separating uranium from commonly associated impurities by complexing in aqueous solution.

Apparatus for Chemical Reaction Detection (2,614,645) H. A. Wilhelm—method for following the progress of a reaction within a sealed reaction chamber by means of sonic vibrations.

Current Measuring Device (2,615,063) C. J. Brown—device for measuring minute electric currents such as the target current of an ion accelerator. Capacitor discharges are indicated by a recorder.

Synchrocyclotron (2,615,129) E. M. McMillan—rotating mechanical vacuum capacitor produces frequencies up to 2,000 cps. Deuterons can be accelerated to 200 Mev.

Mass Analyzing Apparatus (2,615,135) W. E. Glenn, Jr.—inexpensive apparatus for rapid and accurate mass analysis of a mixture by controlled oscillation of an ion beam.

Atomic Air Burst Direction Finder (2,615,249) G. A. Allard—a truncated conical painted surface, with azimuth and elevation markings, is mounted on a standard. An axial rod indicates airburst direction by casting a shadow on the inner surface.

Extraction of Cerium with an Organic Solvent (2,615,798) E. C. Pitzer—cerium, in tracer amount of cerium nitrate in aqueous solution, separated by addition of alkali metal dichromate and extraction with aliphatic ketone.

Time-Delay Relay Testing Device (2,615,967) C. B. Gould—circuit and means for testing a time-delay relay.

Stabilizer Arrangement for Cyclotrons and the Like (2,616,042) R. R. Weeks—device for manual and automatic remote control of the operating resonance frequency of a cyclotron, while maintaining frequency stability and ground-reference balance of the dees.

Fast Neutron Dosimeter (2,616,052) G. S. Hurst—counting-rate method, using a hydrogenous-gas-filled proportional counter, for measuring the fast-neutron dose to cell tissue in the presence of gamma radiation.

Method and Apparatus for Measuring Beam Current (2,616,053) M. G. Holloway—method for determining beam current and energy in a charged-particle accelerator, such as a cyclotron.

Disposal of Radioactive Cations (2,616,847) W. S. Ginell—method of disposing of radioactive fission products in solution by absorption on a cation-exchange mineral, heating the mineral to 705–1,100° C, and burying the heated clay.

Coincidence Circuit (2,617,042) L. F. Wouters—coincidence circuit includes two photomultiplier tubes for impressing signals upon the deflecting plates of a cathode-ray tube and means for indicating pulses of equal phase and magnitude.

Radiation Detector Circuit (2,617,946) B. L. Weller—detector includes an ion chamber having a central collecting electrode, cylindrical electrode, and a guard ring. Potential applied to the ring is equal to that of collecting electrode. An inverse-feedback-circuit amplifier increases the stability when measuring small currents.

Apparatus for Supplying Charge Material to Mass Spectrometer (2,618,750) W. L. Parsegian, C. M. Stevens—means for rapidly and economically introducing non-gaseous samples into the evacuated interior of a mass spectrometer without interrupting the vacuum.

Fluid Flow Control System (2,619,107) C. B. Graham—system for automatically controlling the supply of a liquid medium, such as liquid nitrogen, to a cooling trap. The device is actuated by the vapor pressure of the controlled liquid.

Automatic Drift Corrector (2,619,552) Q. A. Kerns—the circuit periodically samples the drift voltage of a d-c amplifier, and develops and applies a corrective voltage of proper phase.

Adjustable Electrode Support (2,619,609) J. D. Reid—support permits adjustment along planes at right angles to each other and rotational adjustment so that the electrode slits may be aligned with the ion slits of the ionizing chamber.

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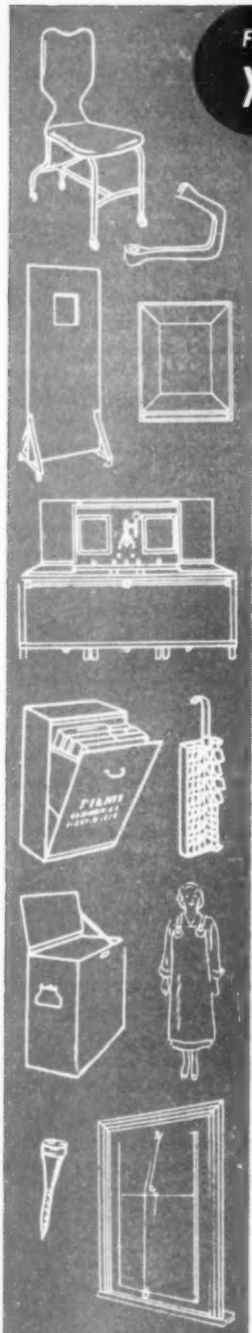


Bar-Ray Installations at Brookhaven National Laboratory

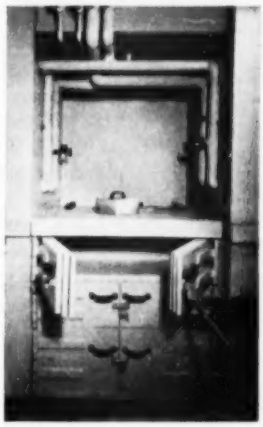
One of the most important approaches to adequate employee protection is the proper design of equipment and fixtures to provide maximum amount of shielding possible. The Isotope Laboratory in the Biology Department at Brookhaven is an example of such design. Plans for this lab were prepared by the Architectural Planning Division of Brookhaven National Laboratory and built complete and installed, as prime contractor, by Bar-Ray. Part of these installations are shown on this page.

RADIOISOTOPE FUME HOOD

The hood on the left is one of four Bar-Ray hood installations, 4' deep × 8' long. Stand is of 3" I beam. Sub-surface top is 4" thick steel slap to shield worker's legs and feet. Finished inside working surface and interior walls and ceilings asbestos cement panels . . . exposed sides laminated with 2" lead and two ¼" steel plates.

Spring balanced safety glass sash and remote service lines for gas, air, hot and cold water: fluorescent lighting, hardwood utility cabinets below working surface.

RADIOISOTOPE STORAGE CAVE



A storage cave (right) between two of the hoods, consists of six steel doors, each three inches thick on heavy ball-bearing strap hinges. Behind these steel doors radioactive materials are stored. On the top shelf which is 4" solid steel, are eight solid steel plugs, 4" thick and 9" square, shown at left, to cover pipes extending down into the ground some twenty feet. The space surrounding these pipes and the walls of the storage cave are solid dense concrete. Access doors introduce a radioactive source directly from the storage area.

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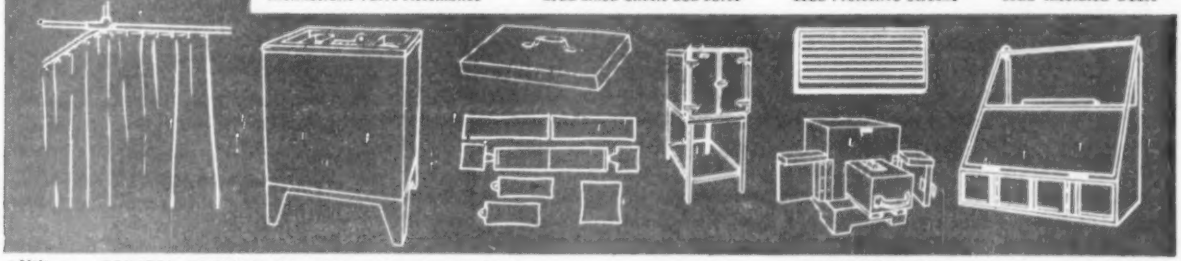

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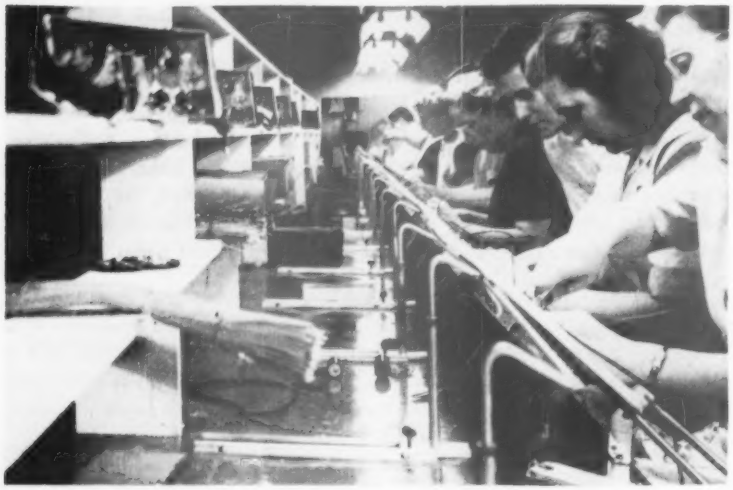
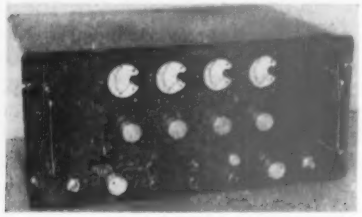


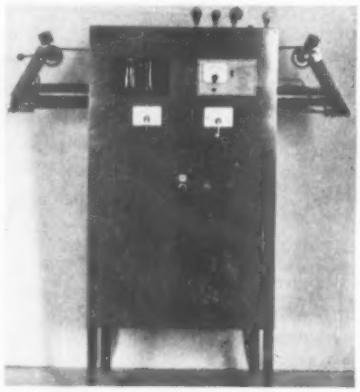
"Building Blocks" Provide Flexible Counting Systems

Detectolab, Inc., 6544 Sheridan Rd., Chicago 26, Ill. Integrated counting systems, based on 15 electronic "building blocks," are described as a completely new line of nuclear instruments. In 30 days, 546 of the units were assembled on the production line shown above. These units, each a fundamental circuit constructed on a $5\frac{1}{4} \times 19$-in. panel, can be combined to fill experimental needs. As an example, if a scale-of-32 G-M counting instrument is required, these units would be ordered: models DV4 plate supply, DS2 scaler, DV12000 power supply, and DZ5 control panel. For gamma counting, these units could be added: models DP2 scintillation detector, DA3 pulse amplifier, and DS2 scaler. Also available are G-M and other detection-type tubes. (P-1)



Preset Counters

Digital Instrument Co., Inc., Box 1246, Coral Gables, Fla. The model 333 preset counter may be set from 0 to 999 and the model 334, from 0 to 9,999. Recycling can be obtained at speeds up to 20,000 cps; the counter operates as a standard counter up to 100,000 cps. Relay contacts are available for control functions, and direct coupled output for electronic control and gating. (P-2)



Hydrogen Furnace

Stewart Engineering Co., Box 145, Soquel, Calif. The model 3 controlled-atmosphere furnace is designed for hydrogen-firing and brazing operations in the laboratory. An Inconel-tube muffle heats the furnace to 1,000° C in 5 min. A four-way valve selects hydrogen, dry hydrogen or nitrogen; a two-way valve selects either humidified or dry atmosphere. A hydrogen flow meter is calibrated from 0 to 75 ft³/hr. Mica windows are provided on the loading and unloading ends; the doors automatically turn off the gas supply when opened. A cooling section is built on one end for faster cooling. (P-3)

C^{14} Reference Sources

Nuclear Instrument and Chemical Corp., 229 W. Erie St., Chicago 10, Ill. Sheets of thermoplastic polymethylmethacrylate, labeled with C^{14} in the polymer molecule, are available in concentrations of 0.1, 1.0 and 10.0 μc/gram. The material is said to be chemically stable, mechanically durable, and uniform in specific activity. The sheets can be burnt to CO_2 as a reference standard for gas counters. (P-4)

Scintillation Detector

Nuclear Instrument and Chemical Corp., 229 W. Erie St., Chicago 10, Ill. The model DS-1 scintillation detector, for γ-ray counting, has a NaI(Tl) crystal. Plateau length is about 200 volts. With the external shield in place, efficiencies of 33% and 40% are obtainable with Co^{60} and I^{131}, respectively. The detector has a removable directional shield and a built-in preamplifier which provides an output pulse in excess of $\frac{1}{4}$ volt. (P-5)

Radioactive Pharmaceuticals

Abbott Laboratories, North Chicago, Ill. The following radioisotopes are available in pharmaceuticals for therapeutic purposes of biochemical studies: I^{131}, P^{32}, Au^{198}, Cr^{51}, S^{35}, Fe^{59}, Ca^{45}, and N^{15}. All solutions are sterile, assayed, and reported as of stated hour and date. (P-6)

Digital Recorder

Beckman Instruments, Inc., Berkeley Scientific Division, 2200 Wright Ave., Richmond, Calif. The series 1550 dig-

Every Top Management Man... In Every Industry

SHOULD BE ABLE TO ANSWER THESE QUESTIONS ABOUT A MOST CRITICAL EMERGENCY IN OUR COUNTRY'S AFFAIRS

Q. Why is iron and steel *scrap* a matter of importance to me?

A. Steel for our country's military program and civilian economy is being produced at the annual rate of 107,000,000 tons in 1951 . . . 119,500,000 tons expected in 1952. Steel-making capacity is being increased now to meet those quotas.

What Do I Get For My Scrap?

In addition to being paid for your scrap, you remove nuisance inventory from your plant—saving valuable floor space. Also, you have a better chance of *getting* new steel or steel products. But, *most important*—you help alleviate a dangerous condition threatening our country's capacity to rearm and satisfy civilian requirements at the same time.

Q. How does scrap figure in the production of steel?

A. Steel is composed, generally speaking, 50% of pig iron, 25% of "production" scrap (that is, the scrap which is produced as a by-product of steel-making) and 25% of "purchased" scrap.

Q. Is scrap getting scarce?

A. Yes. The supply of *purchased* scrap is not increasing fast enough to meet the needs of increasing steel production.

Q. What if the needed scrap isn't obtained?

A. Open-hearth furnaces will not be able to operate at capacity. That will mean a loss of steel production . . . and fewer products made of steel.

Q. Why not use pig iron instead of scrap?

A. Every ton of scrap conserves approximately 2 tons of iron ore, 1 ton of coal, nearly ½ ton of limestone and many other vital natural resources—to say nothing of the extra transportation facilities that would be otherwise required.

Q. How can *more* scrap be furnished?

A. By everybody pitching in—as we always do in every emergency—and searching out all possible sources of scrap.

Q. What are these sources?

A. Metal-fabricating plants normally turn over to scrap dealers the scrap left from machining. But there's not enough of this to fill our present enormous need. So everybody—both in and out of the metal-fabricating industries—must sell scrap in the form of *idle metal.*

Every pound of idle metal is needed to keep our steel mills operating at top capacity. Sell your idle metal to a local scrap dealer right away.

What Do I Do *First*?

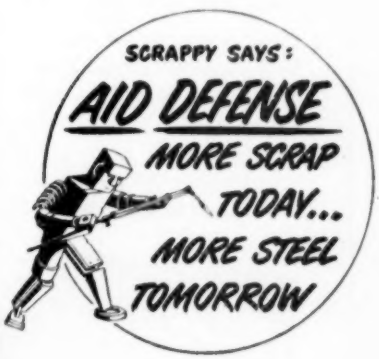
Write for free booklet. It tells how to set up a Scrap Salvage Program in your plant. Thousands of plants are cooperating. Do *your* part now! Address Advertising Council, 25 West 45th Street, New York 19, N. Y.

Q. *We* don't *produce* scrap—how can *we* help?

A. Scrap is any kind of iron and steel that's gathering dust—obsolete machines or structures, jigs and fixtures, pulleys and wheels, chains and track, valves and pipe—*anything* with rust on it or dust on it. Non-ferrous scrap is needed, too.

Q. What do we do with it when we find it?

A. Use your normal channels or get in touch with a recognized scrap dealer.



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ital recorder, composed of a readout unit and a printing recorder, operates from nuclear scalers and other electronic totalizing devices at a maximum cycling rate of one printout per 0.8 sec. The indicating capacity is 3, 4, 5, or 6 decades. Visual display time and counting period are controlled by the counting instrument. (P-7)

Detector Charger

Chatham Electronics Corp., 475 Washington St., Newark 2, N. J. The radiac-detector charger is a portable means of charging pen-type dosimeters. It is completely self-contained and does not require tubes or batteries. Polarity is dependent upon direction of rotation; if a dosimeter is overcharged, it may be zeroed by changing direction of turning. The charger delivers 10^{-8} amperes with output up to 3,000 volts, positive or negative polarity. (P-8)

Humidity-Testing Cabinet

Murphy and Miller, Inc., 1326 S. Michigan Ave., Chicago 5, Ill. This humidity-testing cabinet supplies 20–95% relative humidity in the range 35–185° F. Working space is 27 ft³.

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Consists of two basic electrical circuits, both normally open. Momentary closure of the counting circuit advances indexing device one step. Momentary closure of print circuit causes unit to print accumulated count. Automatic reset to zero available. Wide variety of timing mechanism available as standard equipment.

Unit may be furnished to record elapsed time: 1/10 minute, 1/100 minute, 1 second and 1/10 second. Counting unit may be equipped for direct drive from rotating shaft to count revolutions in units of 1/10. Write for circular SC-24.

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STREETER-AMET COMPANY
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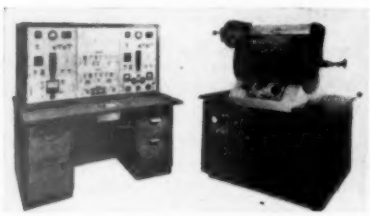
Fast temperature regulation and elimination of condensation are claimed. The unit has a glass viewing panel, hand ports, forced air circulation, and six electrical leads into the working space. A time-schedule control system for presetting dry and wet-bulb temperatures is optional. (P-9)

Automatic Burettes

Scientific Glass Apparatus Co., Inc., 100 Lakewood Terrace, Bloomfield, N. J. Automatic burettes for acids, model TJ-715, and for alkali solutions, model TJ-740, are similar to Scientific's standard automatic burettes but have a solid Teflon plug which prevents sticking or binding. The joint is Teflon-coated so that the burette cannot freeze to the bottle. (P-10)



Beta-Ray Spectrometer

LKB-Produkter Fabriksaktiebolag, Stockholm 12, Sweden. This beta-ray spectrometer, the first commercially produced model, was designed by Dr. Hilding Slatis and Dr. Kai Siegbahn at the Nobel Institute for Physics in Stockholm. Using a magnetic lens, it can focus a maximum energy of 7 Mev. The magnetic field focuses electrons on a G-M tube and also to an intermediate annular image. A slit in the plane of

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JUST PUBLISHED

MICROMETEOROLOGY

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Just Out

MESON PHYSICS

A concise account of theoretical and experimental knowledge, giving results entirely based on latest work with large accelerators and cosmic ray investigations. Presents experimental results within the framework of meson theory where possible. Explores promising lines for future research. By **Robert E. Marshak**, Chm., Dept. of Physics, U. of Rochester. 378 pp., 6 x 9, 105 graphs and diagrams, $7.50.

IONIZATION CHAMBERS and COUNTERS

Experimental Techniques. A reference book for researchers. Covers the behavior of free electrons and ions; the operation of ionization chambers; detectors. A volume in the National Nuclear Energy Series. By **Bruno B. Rossi**, Prof. of Physics, MIT, and **Hans H. Staub**, Prof. of Physics, Stanford U. 243 pp., 6 x 9, $3.25.

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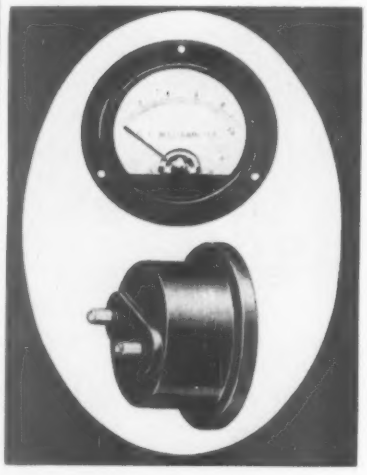
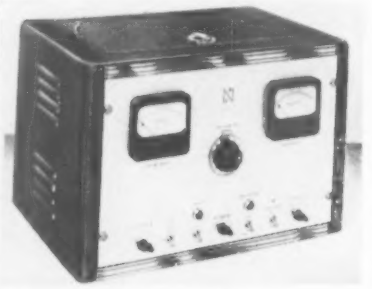
the image defines the resolving power of the spectrometer. With a resolving power of 4%, transmission of 8% of the total radiation is obtained. The spectrometer is equipped with a vacuum system, sample port with sluice, two scalers, and a coincidence scaler. (P-11)



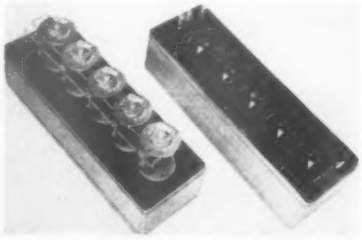
Ruggedized Meters

The Hickok Electrical Instrument Co., 10584 Dupont Ave., Cleveland 8, Ohio. The meter movement of these ruggedized meters is rigidly held in a vibration-proof mounting. Ammeter ranges are 0–50 μa up to 50 amperes, d-c. Ranges of d-c voltmeters, at 1,000 ohms per volt type, are 0–1 through 800 volts. Rectifier-type a-c meters have these ranges: microammeters, 0–50 through 1,000; milliammeters, 0–1 through 5; and voltmeters, 1,000 ohms per volt type. (P-12)



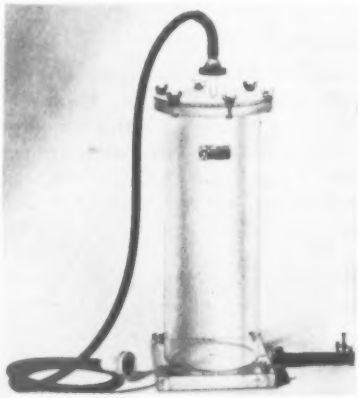
Counting-Rate Meter

Nuclear Research and Development, Inc., 6425 Etzel Ave., St. Louis 14, Mo. The model CRM-500 scintillation counting-rate meter is normally supplied with counting-rate multiples of 1,000, 5,000, 10,000, 20,000, and 50,000 cps; scales up to 500,000 cps can be supplied. A fast-pulse amplifier, with a 0.25-μsec rise time, provides variable amplification up to 1,500. Discrimination is from −100 to +50 volts. The power supply is variable from 500 to 1,800 volts. (P-13)



Resistance Boxes

The Daven Co., Dept. RB, 191 Central Ave., Newark, N. J. The type 750 resistance boxes are assemblies of two or more type 275 decade units. The resistance elements are isolated by a copper lining in contact with a metal panel. The switch consists of three independent silver-alloy "U" blade brushes having independent spring-wiping action. (P-14)



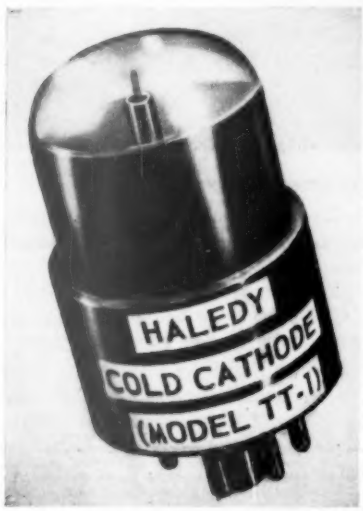
Ion-Exchange Reactor

Enley Products, Inc., 254 Pearl St., New York 38, N. Y. This low-cost ion-exchange reactor is claimed to be suitable for all ion-exchange processes, including water demineralization. The reactor, a basic unit of a modula system, is available in two sizes and three heights. Used in series, a capacity of up to 12,000 gal can be provided. Also available is a regenerator tube which, attached to the reactor, allows for backwashing of resins. (P-15)

Spectrometer with G-M Tube

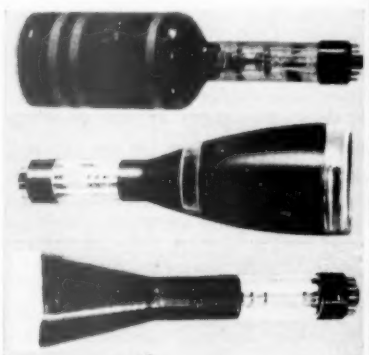
Solus-Schall, Ltd., 18 New Cavendish St., London W. 1, England. The no. 50200 X-ray spectrometer, which pro-

vides instantaneous readings, includes a G-M counter and a diffraction goniometer. Single crystals are measured quantitatively by the Bragg method; polycrystals may be measured by the Debye-Scherrer method. The counter may be swung manually or mechanically through 360 degrees. The range extends to a diffraction angle on both sides of 86 degrees 30 min with an accuracy of ±1 min of arc. (P-16)



Cold-Cathode Tube

Haledy Electronics Co., 57 William St., New York, N. Y. The TT-1 cold-cathode triode operates directly from a-c or d-c lines and is unaffected by temperature. Required grid current is less than 1 μa and input impedances of up to 100 megohms can be used. Circuits employing the TT-1 can be built for an amplification of 2¼-million or more. (P-17)



Cathode-Ray Tubes

Instrument Division, Allen B. Du Mont Laboratories, Inc., 1500 Main Ave., Clifton, N. J. The types 3WP, 5ADP and 5XP-A cathode-ray tubes are

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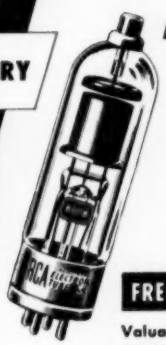

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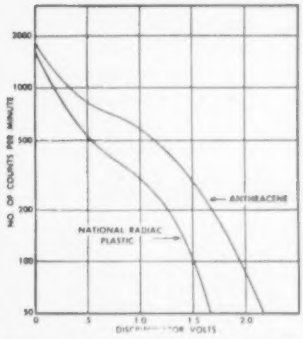

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Comparison with anthracene crystal of same weight:

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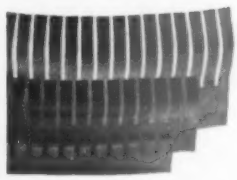

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Eimac

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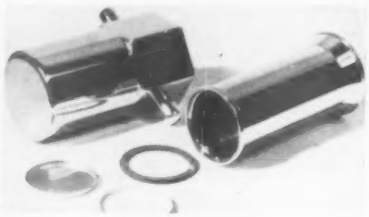
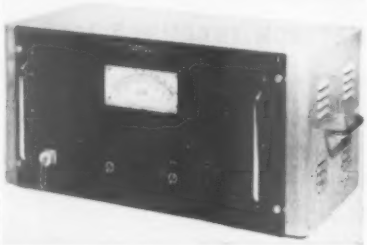
San Bruno, California

claimed to provide more precise measurements than have previously been available. The tubes are said to offer 50% reduction in critical tolerances for deflection sensitivities and grid cutoff, 300%-improved perpendicularity between X and Y deflection plates, and improved sensitivity on both axes, and reduced parallactic error. Characteristics such as deflection linearity, pattern distortion, modulation, line width and light output are specified. (P-18)



Centrifuge Tube

Atomlab, 489 Fifth Ave., New York 17, N. Y. The Atomlab-Ekstein centrifuge tube collects radioactive precipitates directly on standard 1¼-in.-diameter sample pans. The precipitate is said to be deposited evenly, insuring counting reproducibility. Up to 8 tubes can be spun simultaneously. A stainless-steel cylindrical liner and attached sample pan are inserted into a leakproof trunnion cup which fits onto a standard clinical centrifuge head. (P-19)



High-Voltage Supply

Isotope Developments, Ltd., Finsbury Pavement House, 120 Moorgate, London, E. C. 2, England. The type 532 high-voltage power supply is designed for radiation detectors. Output is continuously variable over the ranges 300–750, 700–1,500, and 1,200–3,000 volts at 3 ma; polarity is reversible. Regulation is less than 0.05% change for 10% change in input. Output ripple is less than 0.03 volt rms; short-term drift is less than 0.1% for 10 hr; and output impedance is less than 500 ohms. (P-20)

Chromatographic Cabinet

Berkeley Chromatography Division, University Apparatus Co., 2229 McGee Ave., Berkeley 3, Calif. The model B300 chromatographic cabinet is designed for constant-temperature work; it may be used for the ascending or descending analysis technique. The unit accommodates strips, sheets, or ten 18¾ × 22½-in. filter papers. The cabinet is stainless steel, fully insulated, and airtight. (P-21)

INDUSTRY NOTES

▶**Abbott Laboratories, Isotope Division,** Oak Ridge, Tenn., made its thousandth shipment of radioactive drugs on Dec. 2, 1952.

▶**Industrial Division of Minneapolis-Honeywell Regulator Co.,** Philadelphia, has named O. B. Wilson industrial instruments sales manager.

▶**Landsverk Electrometer Co.,** because of increased business, has moved from its former location in Burbank to new quarters at 550 West Garfield Ave., Glendale, Calif.

▶**Walter Kidde Nuclear Laboratories,** 140 Cedar St., New York 6, N. Y., has named J. H. Frankfort as chief project engineer for the laboratories. Mr. Frankfort has been engaged in nuclear work with the H. K. Ferguson Co. and du Pont.

▶The address of **W. A. Kerr,** general manager of Tracerlab, Inc., is 130 High St., Boston 10, Mass., and not as erroneously reported in the January issue.

LITERATURE AVAILABLE

Humidifiers. "A Few Facts About Humidification" discusses humidity problems and describes line of humidi-

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fiers. *Abbeon Supply Co., 179-15 Jamaica Ave., Jamaica, N. Y.* (*L-1*)

Potentiometers. Bulletin describes precision potentiometers which are easily ganged. *Servotrol Co., 114 W. Illinois St., Chicago 10, Ill.* (*L-2*)

"Electrical Noise in Wire Wound Potentiometers." Paper presented by I. J. Hogan, IRE convention, 1952. *Helipot Corp., 916 Meridian Ave., South Pasadena, Calif.* (*L-3*)

Piston diaphragm pump. Bulletin 300 gives information on controlled fluid-flow pumps. *Lapp Insulator Co., Inc., Process Equipment Division, Le Roy, N. Y.* (*L-4*)

Tubes for electronic design. Revised edition of "Preferred Tube Types for New Equipment Design." *Commercial Engineering, RCA Tube Department, Harrison, N. J.* (*L-5*)

Analytical balance. Gram-atic balance, described in bulletin, is direct-reading and eliminates handling of weights. *Fisher Scientific Co., 717 Forbes St., Pittsburgh, Pa.* (*L-6*)

Solenoids. Catalog DCS3-1952 covers line of d-c solenoids. *Cannon Electric Catalog Dept., 420 W. Avenue 33, Los Angeles 31, Calif.* (*L-7*)

Recorders. Bulletin gives specifications on direct-writing recorders. *Sanborn Co., 38a Osborn St., Cambridge, Mass.* (*L-8*)

Pulse generator. Brochure describes model B-2 general purpose generator. *Rutherford Electronics Co., 3707 S. Robertson Blvd., Culver City, Calif.* (*L-9*)

Mass spectrometer. Bulletin CEC-1800B discusses uses and characteristics of model 21-103A mass spectrometer. *Consolidated Engineering Corp., 300 N. Sierra Madre Villa, Pasadena 15, Calif.* (*L-10*)

Nucleonic equipment. Condensed catalog gives data and prices of radioactivity instrumentation. *Nucleonic Corp. of America, 497 Union St., Brooklyn 31, N. Y.* (*L-11*)

Testing service. Folder lists 80 methods for testing, inspecting and analyzing products. *American Standards Testing Bureau, Inc., 44 Trinity Place, New York 6, N. Y.* (*L-12*)

Variable speed changers. Bulletin 99 describes miniature, continuously adjustable speed changers. *Metron Instrument Co., 432 Lincoln St., Denver 9, Colo.* (*L-13*)

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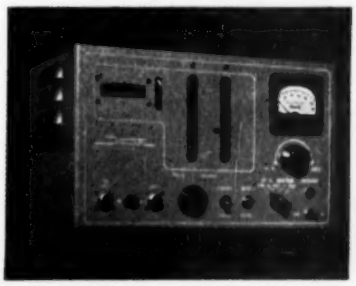

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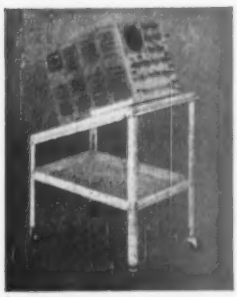

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Model 204B Linear Amplifier — for use with ionization chambers, scintillation and proportional counters. Rise time to 0.2 microseconds, gain to 15,000. Three-position band width switch. Dual attenuator, precision calibrated pulse amplitude discriminator. Low and high level outputs, self-contained power supply, provision for preamplifier.

Also Model 204C — similar to 204B with separate input time constant and rise time controls.

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Also Model 316 — same as Model 306 except with 7"x19" rack mount panel; and Model 326, two units, either polarity, on single 7"x19" rack panel.

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Also Model 503C Two Channel Anticoincidence Analyzer — for low level GM tube measurement; with dual regulated H.V. supplies, scale of 16 and register.

PULSE HEIGHT ANALYZERS

Model 510 Single Channel Differential Pulse Height Analyzer — for pulse amplitude distribution studies, with channel base line adjustable to 100 volts and window settable from 0 to 7 volts. Can be used with Model 204 Linear Amplifier and any of Atomic's Scalers to meet many nuclear laboratory needs.

Also Model 520 Twenty Channel Differential Pulse Height Analyzer. The complete answer for a complete analyzer.

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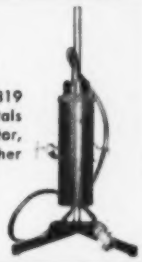

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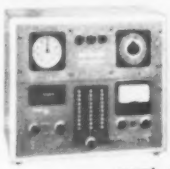

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